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CONSIDERATION OF THE DEPTH OF THE MOTIONLESS SURFACE NEAR THE GRAND BANKS OF NEWFOUNDLAND

By

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In physical oceanography the admitted limitations of the Bjerknes circulation theorem sometimes are lost sight of and therefore the current trend of inquiring emphasis on these limitations is encouraging. The intelligent interpretation of dynamic calculations and the determination of absolute current directions and velocities therefrom, depend upon a knowledge of the location and shape of a motionless reference surface. In the past the arbitrary selection of isobaric surfaces for reference has been the resort to an approximation found useful in the absence of more definite knowledge regarding the true location and shape of such a motionless surface or surfaces. In recent years various oceanographers have proposed various non-spheroidal reference surfaces such as the oxygen-minimum layer, and a surface approximating an isentrope of constant vertical stability. The state of our knowledge has not yet reached the point where we can define such a surface which is universally applicable. Until that stage of development is reached each unique region must be dealt with individually and the several particular solutions may help in ultimately laying bare that general solution.

In the southern part of the Labrador Sea the oxygen minimum surface cannot be used since it is not present. Observation and experience of the International Ice Patrol has shown that the direction and velocity of the surface currents as indicated by the drift of icebergs are essentially in agree-

* Contribution No. 230.

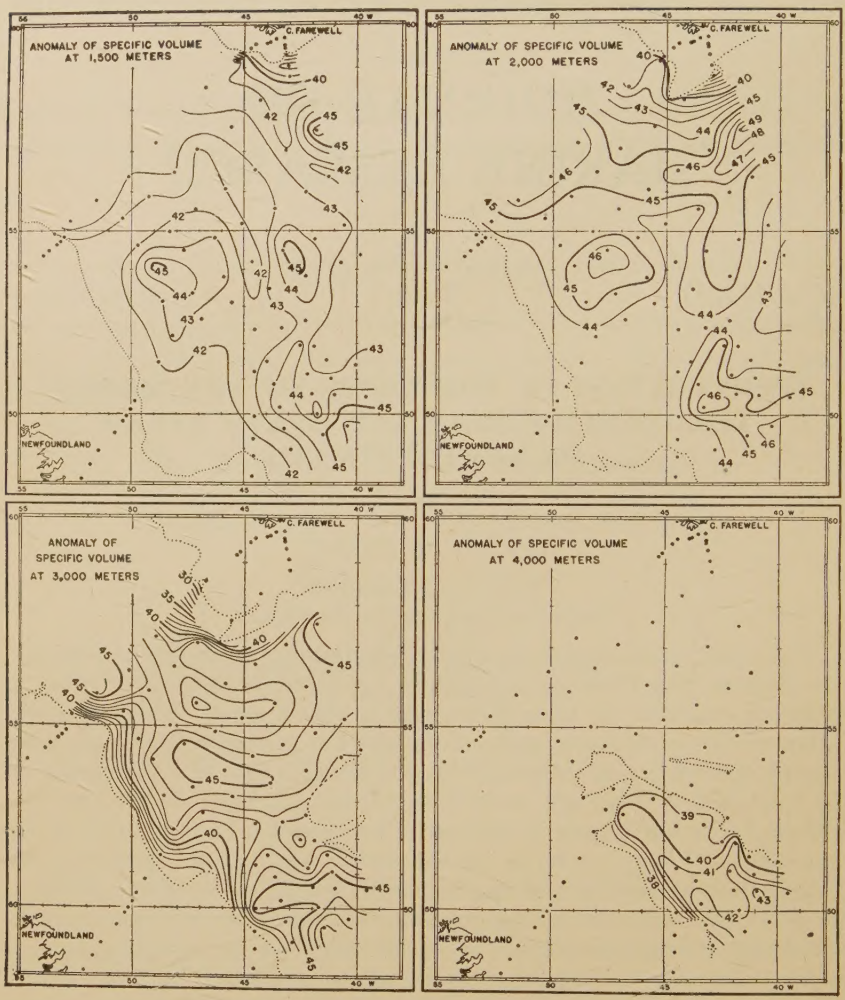

Figure 53. Horizontal distribution of anomaly of specific volume.

ment with dynamic topographic maps referred to the 1500-decibar surface. Prior to 1935 deeper reference surfaces were not used for this region chiefly because of the errors which would have been introduced through necessary extrapolations in the many cases where observations did not extend to deeper levels. However, during the summer of 1935 a network of stations in this area were all occupied to as near bottom as was practicable and the question arose as to what reference surface would be the best.

In order to find the most nearly motionless level in the area as a whole the least variability in vertical differences in dynamic height for any 500-meter layer was selected as a criterion. The investigation showed that the desired level was at about 2000 meters. The method was then checked by inspection of horizontal gradients of anomaly of specific volume. Figure 53 shows the horizontal distribution of anomaly of specific volume for the 1500-, 2000-, 3000-, and 4000-decibar surfaces and demonstrates that the horizontal gradients are least in the 1500- and 2000-decibar surfaces. It will also be seen that with the exception of the region immediately south of Cape

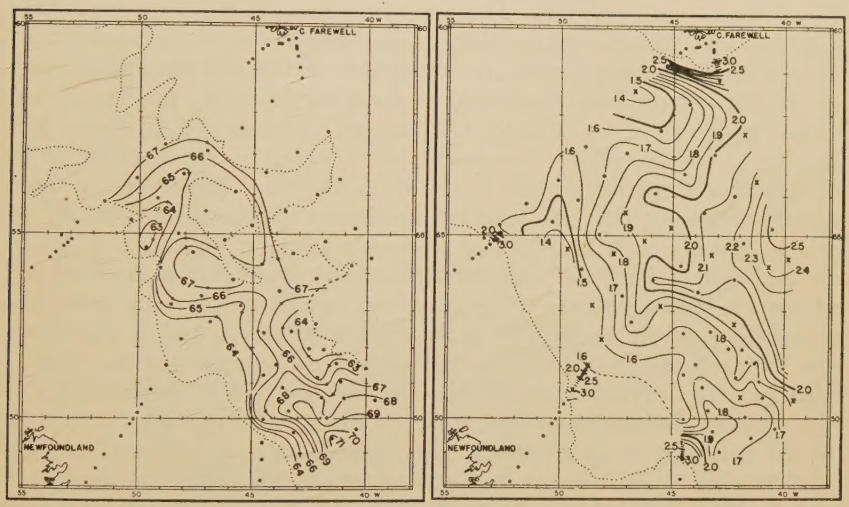

Figure 54. At left: Dynamic topography at 3,500 decibars relative to 2,000 decibars. At right: Potential bottom temperatures.

Farewell, the 2000-decibar surface is indicated as most nearly motionless on the basis of this criterion. Such a criterion rests on an assumption which at that time was reasonable but without proof. Restated, the assumption was that the surface in which the velocity was most nearly uniform was also the surface in which the velocity was most nearly zero.

Deep level dynamic topographic charts were then drawn with reference to the 2000-decibar surface and these gave a circulation picture of the deep water consistent with other criteria of the circulation of the deep and bottom waters of the Labrador Sea. Admittedly, because of the small density gradients involved and because of the probably undulatory character of the motionless surface if one exists, the accuracy of deep level current maps is highly questionable as to velocity. It is believed, however, that the indi-

cated directions of flow are reliable in the main. One bit of evidence confirming these maps, and therefore the selection of the motionless surface, is to be found in examining the bottom temperatures. From the material of this survey it was possible to construct a reliable chart of the potential temperature at bottom. Figure 54 shows the dynamic topographic map of the 3500-decibar surface relative to 2000 decibars and the potential bottom temperatures for depths greater than 1500 meters. Each part of this figure will be seen to indicate the southward movement of water along the American side of the basin.

During the summer of 1937 an adjacent area to the south, east of the Grand Banks, was surveyed. At many of the stations the observations extended to 4000 meters. Although these stations were so widely spaced that it is not possible to deduce from them detailed patterns of circulation, they nevertheless afforded the opportunity of studying the major features. In a manner similar to that used in the 1935 survey, the horizontal distribution of anomaly of specific volume was examined by means of the construction of horizontal sections for several of the deeper levels. Inspection of these sections indicated that the smallest horizontal gradients of anomaly of specific volume occurred at 2000 or 2500 meters depth. Again using this as the criterion of least motion, the 2000-decibar surface was selected for reference in the construction of dynamic topographic maps. In Figure 55 is shown the resulting topography at the surface of the sea and at 3500 decibars both referred to the 2000-decibar surface. The picture of the circulation at the sea surface is in accord with the direction of drift indicated by the wire angle at stations where light wind or calm weather prevailed, and with the set indicated by astronomical observations on runs between stations. Further verification is found in the depth of the 10° isotherm. Iselin (*1*) has found this to be a convenient indicator of the circulation in the western North Atlantic and examination of those stations taken in or near the Atlantic Current shows a notable correspondence between the contour lines of this thermal surface and the indicated course of the dynamic isobaths.

Examination of the anomalies of dynamic height at levels below 2000 decibars with reference to that surface indicated increasing relative velocities to 3500 decibars and a decrease from 3500 to 4000 decibars. In the preceding discussion of the 1935 survey of the adjacent area to the north it was pointed out that the deep water was moving southward along the American side. Here we see the continuation of this southward flow of the deep water past Flemish Cap and continuing as far as latitude 40° N., the southern limit of the survey. Most of the flow continues close in to the edge of the Grand Banks but some of it travels more directly southward along the 41st meridian, being separated from the major portion by a whorl which is roughly concentric with the bottom depression at about 44° N., 42° W.

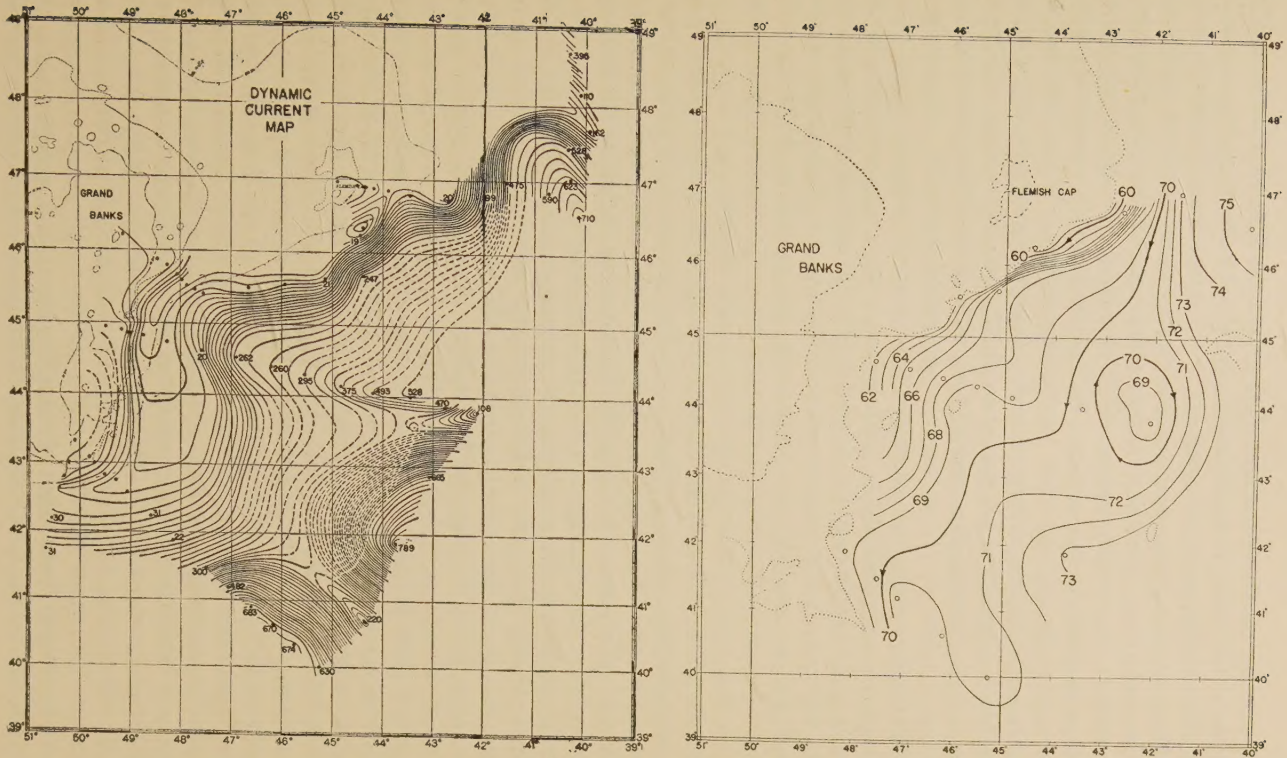

Figure 55. Dynamic topography at the surface and at 3,500 decibars, both referred to 2,000 decibars.

Now a rough check on the assumption that the 2000-decibar surface is most nearly motionless is made possible by the distribution of the isobaths in the 3500-decibar map with respect to the overlying Atlantic Current. The volume of flow of the Atlantic Current past the section east of Flemish Cap, determined by numerical computation and checked by planimeter measurements of a velocity profile, was 39.3 million cubic meters per second relative to the 2000-decibar surface. At 3500 decibars the velocity is greater at this section than in any other part of the survey. If the 2000-decibar surface is motionless the average velocity in this section at the 3500-decibar surface is 6.6 centimeters per second southerly and the average velocity of the water in the rectangular cross section between the 2000- and 3500-decibar levels is taken at 3.3 centimeters per second southerly. However, if the 3500-decibar surface is motionless the average velocity is 6.6 centimeters per second northerly at 2000 decibars; the average velocity in the rectangle is 3.3 centimeters per second northerly; and all of the velocities used in determining the volume of flow of the Atlantic Current above 2000 decibars are too small by 6.6 centimeters per second in which case the volume of flow of the Atlantic Current past this section becomes 39.3 + 25.5 + 9.7 or 74.5 million cubic meters per second northerly.

Now the 3500-decibar map indicates that the deep water velocity past the section running southeasterly from the Tail of the Grand Banks is much less than it is east of Flemish Cap. Again taking the 2000-decibar surface as motionless, the average velocity at the 3500-decibar surface at the southern section is 2.6 centimeters per second southerly, whereas if the 3500-decibar surface is motionless this represents the average northerly velocity at 2000 decibars. If half this figure or 1.3 centimeters per second be taken as the average velocity of the water between the 2000- and 3500-decibar surfaces under the Atlantic Current at this section, the resulting volume of flow between these surfaces is about 5.9 million cubic meters per second, directed northerly if 3500 decibars is the motionless surface and directed southerly if 2000 decibars is the motionless surface. Furthermore, if the 3500-decibar surface is motionless any determination of the volume of flow above 2000 decibars relative to that surface will be based on velocities which are uniformly too low by 2.6 centimeters per second which will result in a discrepancy of 15.8 million cubic meters per second. Thus if the 3500-decibar surface is motionless, and we assume that the Atlantic Current passing the Flemish Cap section is the same as the Atlantic Current passing the southern section, a determination of the volume of flow past the latter section from 0 to 2000 decibars relative to 2000 decibars should give 74.5 − 5.9 − 15.8, or 52.8 million cubic meters per second; but if the 2000-decibar surface is motionless, the result should be 39.3 million cubic meters per second. Numerical computation, again checked by planimeter measurements of a velocity profile of the Atlantic Current past this southern section, actually

showed a volume of flow of 42.8 million cubic meters per second, which is much nearer the figure of 39.3 than the alternate figure of 52.8. Restating these figures in another manner: if the 3500-decibar surface was motionless the Atlantic Current in passing from the southern section to the Flemish Cap section increased from 64.5 to 74.5 or 10 million cubic meters per second which is 15½%, whereas if the 2000-decibar surface was motionless the Atlantic Current decreased from 42.8 to 39.3 or 3.5 million cubic meters per second which is 8%. Considering that we have been discussing only the northern branch of the Atlantic Current and considering the assumption that the volume of flow past the two sections is the same, the foregoing would seem to indicate that the 2000-decibar surface is more nearly motionless than the 3500-decibar surface.

Attention is again directed to the other assumptions made in this transport balance; namely, that the deep water velocities are sufficiently reliable to make the check significant, and that the vertical distribution of the deep water velocity is near enough to being linear for the purpose of the check.

From the dynamic topographic maps of the sea surface and the 3500-decibar surface, as well as other maps not shown, the direction of flow is indicated to have been roughly parallel to the bottom contours at all levels. This is true regardless of the reference surface selected, only the direction of flow along the dynamic isobaths being dependent upon the selection of the proper reference surface. In other words at any level the flow is either from the Tail of the Grand Banks toward Flemish Cap or from Flemish Cap toward the Tail of the Grand Banks. The temperature-salinity correlation was investigated at each end of the area surveyed. All of the observations from depths greater than 1500 meters from the stations comprising the section east of Flemish Cap were plotted and the individual station curves drawn. These are shown at the left in Figure 56. The two broken lines, separated by about 0.03 ‰ salinity, represent approximately the range of observational error. A similar plot of temperature against salinity was made for all observations from depths greater than 1500 meters from the stations comprising the section running southeasterly from the Tail of the Grand Banks and is shown in the middle of Figure 56. Again the individual station curves have been drawn and the envelopes indicated by broken lines. The separation of the envelopes is again about the range of observational error except in the vicinity of about 3.25°, where the characteristic shape of the individual station curves require a lower-salinity hump. From these two plots have been derived the mean curves representing the temperature-salinity correlation for the two extreme edges of the survey, along the course of the current, for depths greater than 1500 meters, and shown at the right in Figure 56. From this it will be seen that the two correlation curves cross and that in the upper part of the figure the water off Flemish Cap is fresher than off the Tail of the Banks, whereas in the lower part of the plot, in the

deeper water, that off the Tail of the Banks is fresher than that off Flemish Cap. Now if we consider that the source of this fresher water of more negative salinity anomaly is the downward-mixing, cabbeling (*5*), mixed water containing Labrador Current water as a constituent and found along the boundary between the Labrador and Atlantic Currents (*3*) (*4*), then the interpretation is that in the upper levels the Atlantic Current is traveling from the Tail of the Banks toward Flemish Cap, which we know to be the case, and that in the deeper levels the water below the Atlantic Current is moving in the opposite direction, from Flemish Cap toward the Tail of the

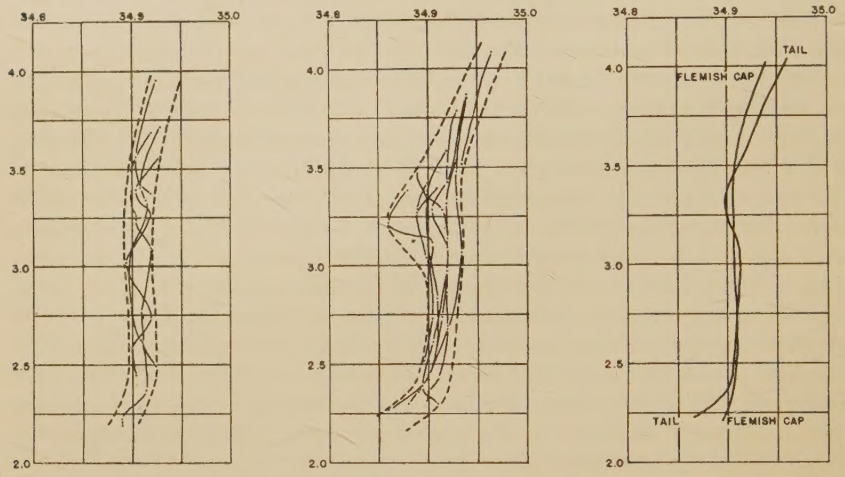

Figure 56. Temperature-salinity correlation for depths greater than 1,500 meters. Left: Stations 2523–2528 occupied July 7–9, 1937, east of Flemish Cap. Middle: Stations 2475–2484 occupied June 22–25, 1937, southeast of the tail of the Grand Banks. Right: Comparison of mean curves.

Grand Banks. The corollary is that at some level in between, the water is motionless and that this motionless level is at about where the two curves shown at the right in Figure 56 cross. The presence of the hump in the curve for the Tail of the Grand Banks makes it difficult to say from this figure where this motionless level is located more exactly than that it is between temperatures of about 2.7° and 3.4° C. which correspond to depths of about 3200 and 1750 meters respectively. This is looked upon as strong evidence in favor of the existence of a motionless surface such as was assumed in the construction of the dynamic topographic maps referred to the 2000-decibar surface, the depth of which surface is within the limits indicated from this consideration of the temperature-salinity correlations.

Because it was indicated, on the assumption of the 2000-decibar surface

as the most nearly motionless, that the most rapid motion of the deep water occurs in the 3500-decibar surface, this surface was selected for the illustrations which have been described. For the same reason and for comparison with the dynamic topography of the 3500-decibar surface referred to the 2000-decibar surface a potential density surface of $\sigma_{t_\varphi} = 27.90$ was selected for an isentropic (*2*) analysis since the depth of this density surface is in the neighborhood of 3500 meters. Potential temperatures at this isentropic surface have been determined and isotherms have been drawn for the same survey from which was derived the deep level current map which has figured in the foregoing discussion. For purposes of comparison, Figure 57 shows this dynamic topographic chart of the 3500-decibar surface relative to 2000 decibars at the left, and the isothermal chart of potential temperature at the surface of $\sigma_{t_\varphi} = 27.90$ at the right. The axis of minimum temperature is the most striking feature of this illustration and has been traced in as a heavy broken line. It indicates the flow of the cold deep water from the Labrador Sea southward beneath the Atlantic Current. This is the same general picture of the circulation of the deep water that is given by the topographic chart at the left. The similarity of the two parts of the illustration is considered to be a further confirmation of the approximation to zero velocity at the 2000-decibar surface since this is the reference surface used in the construction of the dynamic topographic map shown. As was pointed out earlier in connection with the topographic map the stations are so far apart that details of circulation cannot be derived from the map. This is of course also true for the isothermal chart of the isentropic surface shown. All of the isotherms might well be drawn as broken lines to indicate the uncertainty as to their course. However, this much is regarded as certain: that the axis of minimum potential temperature is well defined and the southward flow clearly indicated. There is a choice open as to whether the axis passes east or west of the central station at the north end of the diagram. In the isentropic analysis the axis has been shown as passing east of this central station in order to preserve the simplest diagram. In the dynamic chart the axis seems to pass to the west of this central station. The main point is that the two circulation pictures are in general agreement.

Perhaps it should be emphasized here that the idea of flow along an isentropic surface is subject to the same necessity for proof that confronts the Bjerknes circulation theorem. It is subject to limitations and a very pertinent limitation in the region under discussion is that the flow is not isentropic in regions where cabbeling is taking place. It has already been mentioned that along the boundary of the Labrador Current cabbeling is in evidence. The left hand edge of this isentropic chart is therefore questionable. This presence of cabbeling may be a factor in the reason for the

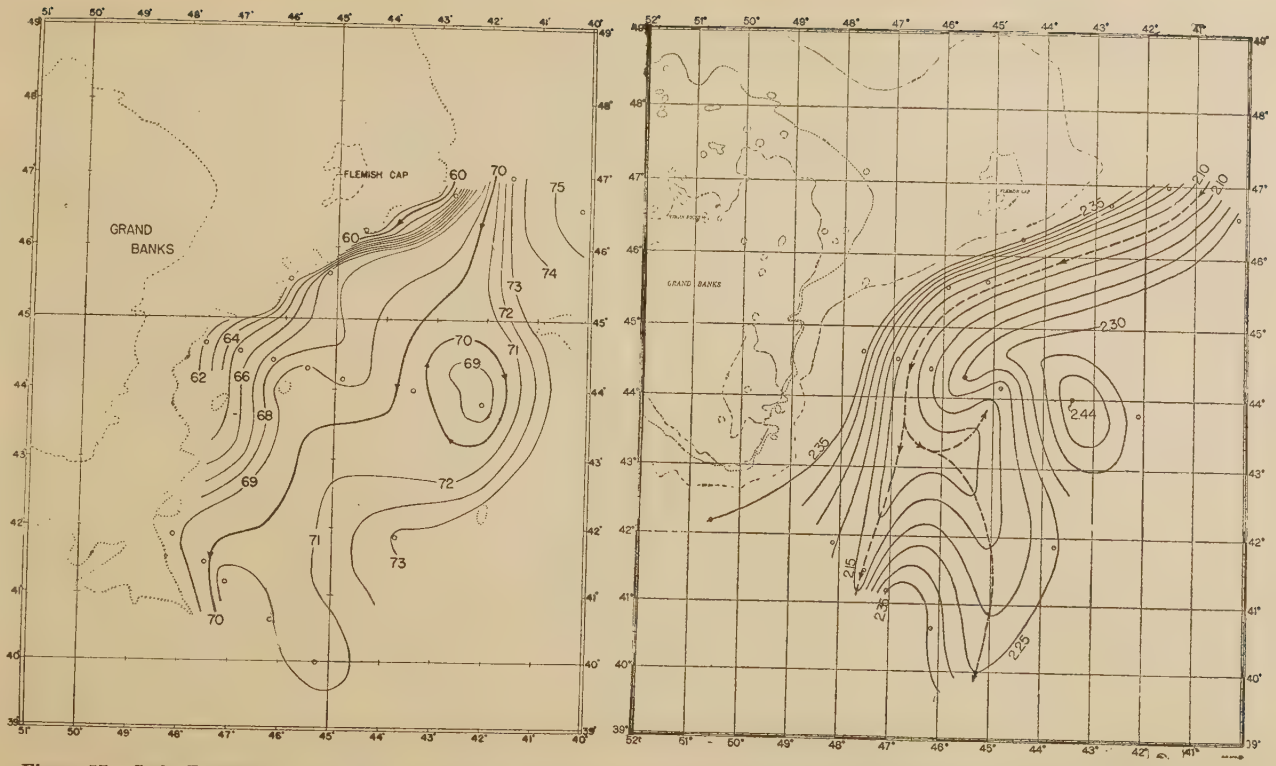

Figure 57. Left: Dynamic topography at 3,500 decibars relative to 2,000 decibars. Right: Potential temperature at isentropic surface of $\sigma_{t_\varphi} = 27.90$.

variable depth of the isentropic surface selected. Figure 58 illustrates the extent of this variation in depth. Here the depth of the isentropic surface has been plotted for each of three sections across the axis of minimum potential temperature. In each case the western end of the section is at the left. The broken vertical lines indicate the intersection of the cold axis with the various sections. The three curves have been so oriented that the intersections with what is regarded as the major cold axis have a common

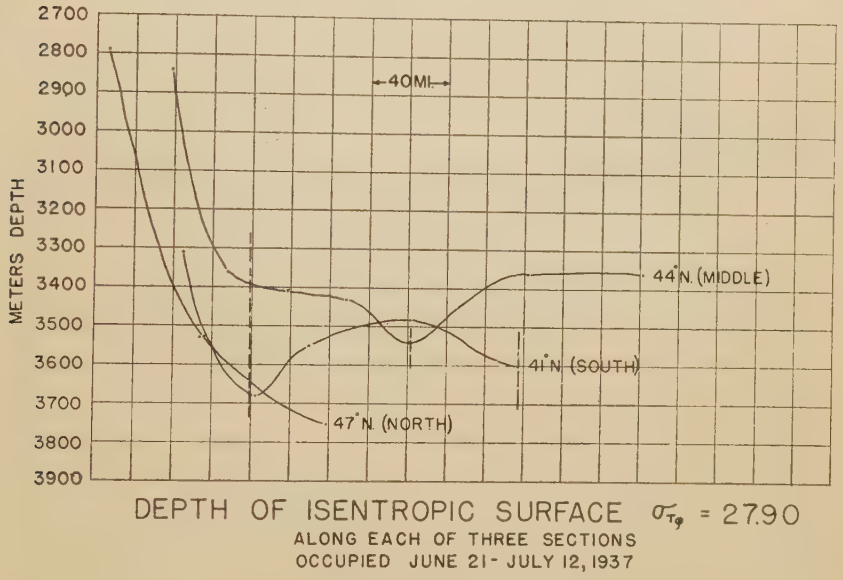

Figure 58. Three profiles through isentropic surface of $\sigma_{t_\varphi} = 27.90$.

abscissa. This illustration shows that in each of the sections the depth of the surface shoals abruptly in approaching the western end. This is noted because it is particularly along the western edge of the figure that cabbeling probably occurs. The figure also illustrates the degree to which the depth of the isentropic surface approaches that of the 3500-decibar surface.

We have now considered a number of indicators all of which are in substantial agreement in support of the existence of a most nearly motionless level at a depth of about 2000 or 2500 meters in the region immediately eastward of the Grand Banks. Summarizing, this evidence is contributed by patterns of flow, bottom temperatures, a volume transport balance, temperature-salinity correlations, and a deep-water isentropic analysis.

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SEA LEVEL DEPARTURES ON THE CALIFORNIA COAST AS RELATED TO THE DYNAMICS OF THE ATMOSPHERE OVER THE NORTH PACIFIC OCEAN

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Considerable attention is being directed at the present time toward fluctuations in sea level as related to the dynamics of the oceans and, to a lesser degree, the dynamics of the atmosphere. Most of the work along these lines, however, has been concerned with seasonal rather than non-periodic variations. Nevertheless, an analysis of sea level data compiled over a period of many years at four California tidal stations indicates that non-periodic fluctuations of considerable magnitude also occur. Since these fluctuations are probably the direct or indirect result of variations in certain meteorological elements, it becomes of interest to investigate the nature of those atmospheric changes that occur simultaneously with changes in sea level.

A preliminary examination of the problem indicated that the sea level variations might be divided into two classes; i. e., (1) local variations of short duration and (2) widespread variations of long duration. The short period variations may be limited to one or two stations on the Pacific coast and are undoubtedly due to local changes in the oceanic circulation. The second class of departures will include those variations of longer duration which appear to affect all stations on the coast. It was soon discovered that it would be impossible to isolate the meteorological factor in the short period local variations by means of the small quantity of oceanographic and meteorological data available due to the complicated pattern of the oceanic circulation in the region immediately off the coast. The widespread fluctuations, however, appear to be due to major changes in the ocean currents over the North Pacific and analyses of mean monthly or seasonal sea level and meteorological data have given positive evidence of a very close relationship between atmosphere and ocean.

Any exhaustive analysis of the relationships between ocean and atmosphere requires complete and accurate data from significant areas of the ocean surface. Unfortunately, both the oceanographic and meteorological data from the North Pacific are very meager and of doubtful accuracy,

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therefore any critical analysis of the problem in quantitative terms is impossible. By the proper selection of mean monthly data when sea level departures are significant, however, it is possible to illustrate some of the more salient features of the atmospheric-oceanic machine.

LaFond (1939) attributes practically all the variations in sea level at these same tidal stations to changes in the density of shore waters above the 500 decibar level and assumes that these changes, themselves, are brought about by alterations in the flow pattern of ocean currents along the immediate coast. Nomitsu and Okamoto (1927) similarly conclude that meteorological changes are of secondary importance when considering sea level departures on the Japanese coasts and endeavor to show that differences in the density of surface waters are primary. Montgomery (1938), working with tidal data from the western North Atlantic, assumes that the major departures in sea level along the Atlantic coast are caused by variations in ocean currents. Palmén (1932), in his study of short period sea level fluctuations in the Baltic, has assumed that the departures are largely caused by local winds (*Windstau*) and has divided these effects into two classes: the component in the direction of the wind or the pure mechanical wind effect (*Windeffekt*), and the component at right angles to the wind or stream-effect (*Strömeffekt*). The present paper is concerned primarily with the *Strömeffekt* since this process is more than purely local and should appear over large areas whereas the *Windeffekt* would probably not appear in the mean monthly sea level data available.

The very fact that sea level departures are so easily accounted for by changes in the density of surface waters would lead us to suspect that these changes are probably directly related to changes in wind currents over ocean surfaces and, as a result, any series of data which shows a relationship between density (or temperature/ or salinity) and sea level is *sui generis* including meteorological effects.

HYDROSTATIC EFFECT OF ATMOSPHERIC PRESSURE

If the sea surface is in a state of static equilibrium with respect to the atmosphere, any change in atmospheric pressure will result in a change of sea level. That is, sea level will be lower with a high barometer and higher with a low barometer. If the departures in atmospheric pressure are measured in inches or millimeters of mercury then the corresponding departures in sea level similarly expressed will bear the ratio 1 : 13.2. Practically all the values of the pressure factor assigned by various investigators approach this figure, although they may be greater or less in partially enclosed seas or bays.

Since the hydrostatic effect appears only when a pressure gradient exists, departures in pressure at any individual station can be used only in a quali-

tative sense but they may be valid if such departures accurately represent numerically equivalent changes in pressure gradient. All of the works examined by the writer have applied an arbitrary correction to the sea level data based upon pressure departures at some one coastal station. A consideration of pressure gradients has been neglected in all cases.

Mean sea level and mean atmospheric pressure for all months of May, 1923–36, are presented in Fig. 59. These data indicate good qualitative

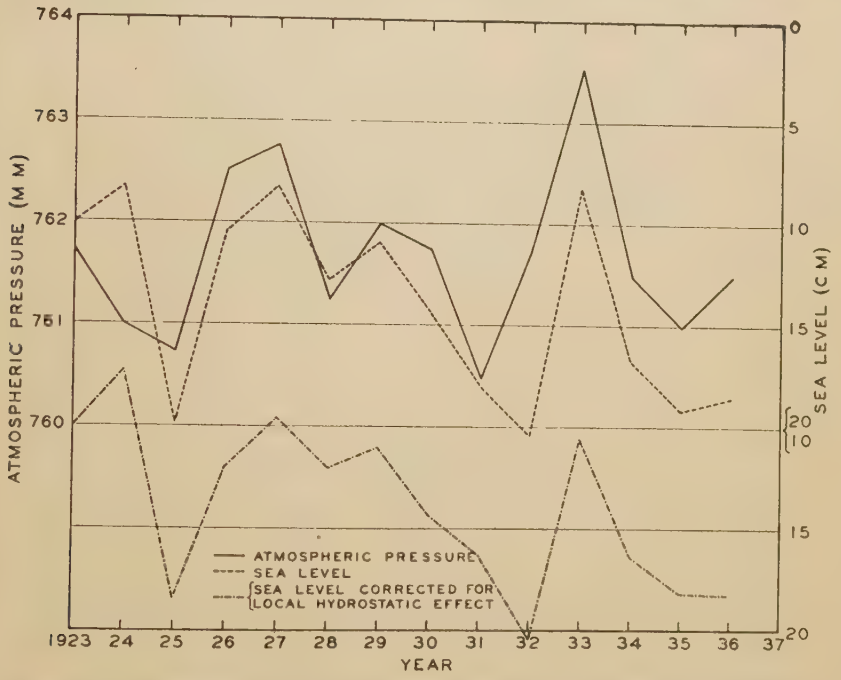

Figure 59. Relationship between atmospheric pressure and sea level at San Francisco for all months of May, 1923–36. Pressure is in millimeters; sea level is in centimeters measured above an arbitrary base line. The dash-dot curve represents the sea level values to which the arbitrary pressure correction has been applied.

agreement between the two elements and it may be observed that the departures are of opposite sign in eleven out of thirteen cases. Departures for a single month in each year were chosen in order to eliminate seasonal effects. The series illustrated was selected at random but other months show the same relationship although it is not so marked during the fall and winter months when the oceanographic and meteorological picture of the North Pacific is considerably more complicated than during the spring and summer months. As shown in Figure 60, however, the actual numerical

departures are highly irregular and the sea level variations far too large to be accounted for by local hydrostatic effects alone. In fact, as illustrated in Figure 59, the sea level data show practically the same variations after the hydrostatic correction has been applied, the process merely serving to

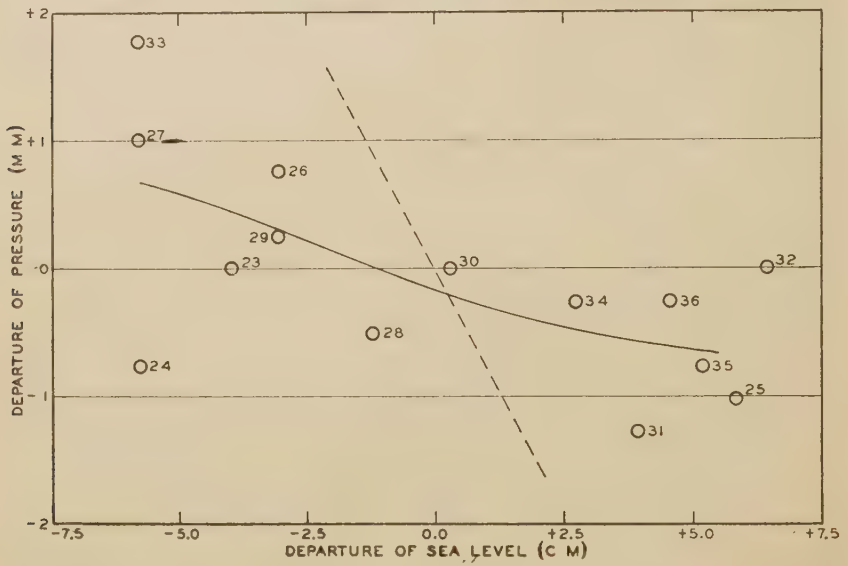

Figure 60. Departures of atmospheric pressure at San Francisco plotted against sea level departures for all months of May, 1923–36. Dashed line represents the pressure departures multiplied by 13.2.

smooth the curve somewhat. It must be concluded, therefore, that one or more of the following three conditions is satisfied:

(1) Pressure departures at coastal stations are indicative of numerically greater departures of similar sign over the sea along the immediate coast.
(2) The pressure departures are accompanied by greater departures of opposite sign over removed portions of the sea surface.
(3) The departures in atmospheric pressure represent widespread meteorological changes which, themselves, serve to alter the dynamic picture of the ocean.

First, with respect to (1). In order to study the monthly pressure departures over the eastern North Pacific, a series of maps was constructed showing mean atmospheric pressure for twenty months when sea level departures at coastal stations were significant. The data were obtained

from the synoptic charts prepared twice daily at the U. S. Weather Bureau in San Diego. Analysis of these maps indicates that departures in atmospheric pressure at coastal stations are usually accompanied by greater departures of similar sign over the sea off the coast but the relationship, quantitatively, appears to be very irregular.

Data for San Francisco are presented in Table I. These figures show that departures in pressure at San Francisco were accompanied by departures of similar sign in the region off the coast to longitude 140° W. in 75% of the

TABLE I

DEPARTURE OF ATMOSPHERIC PRESSURE FROM MONTHLY MEANS AT SAN FRANCISCO AND OVER PACIFIC TO LATITUDE 140° W.

Year	*Month*	*Departure of Pressure at San Francisco (mm)*	*Departure of Pressure Between Lat. 140° W. and Coast (mm)*	*Departure of Pressure Gradient from Normal Between Lat. 140° W. and San Francisco (mm)*
1931	Feb.	−2.3	−1.3	+2.5
1933	"	+2.8	+4.8	+3.0
1933	Apr.	−1.3	+3.0	+6.4
1934	"	−1.0	−1.5	0.0
1935	"	−2.0	−3.6	−0.8
1936	"	+0.2	−2.0	−1.5
1933	May	+1.8	+2.3	+0.5
1934	"	−0.4	−1.0	−1.8
1930	June	−0.1	+2.3	+3.8
1933	"	+0.5	+3.3	+3.0
1930	Aug.	+1.5	−0.5	−4.1
1933	"	−0.5	−0.8	−1.3
1936	"	−0.2	−0.2	−1.0
1930	Oct.	−1.0	−2.0	−2.0
1933	"	−0.8	−2.3	−1.5
1930	Nov.	−0.5	+0.8	+1.5
1933	"	+1.0	+3.6	+2.8
1930	Dec.	+1.3	+1.0	+0.2
1931	"	−2.0	−3.6	−0.5
1933	"	−0.2	−3.6	−5.3

cases examined, and in 80% of these cases the departures off the coast were numerically greater than at San Francisco. These differences are too slight, however, to account for any significant proportion of the effects illustrated in Figure 59.

With respect to (2), i. e., are pressure departures at coastal stations accompanied by significant departures of opposite sign over removed portions

of the sea surface? Any departure in atmospheric pressure, of course, demands corresponding departures of opposite sign over other areas, the problem here being one of regional adjustments within areas where hydrostatic displacements of the sea surface are possible. Clayton (1938) has recently shown that regional adjustments in pressure do not follow any known set law and that the *baroplions* and *baromions*[1] over the ocean appear to be entirely independent of the intensities or locations of the centers of the pressure fields with which they are associated. Analysis of pressure data at permanent stations on the North Pacific by the writer appears to bear out this conclusion. The pressure departures at San Francisco were first compared with corresponding departures at stations on the Asiatic coast of the Pacific. Although there was slight evidence that departures in the two areas tended to be of opposite sign, the data were not conclusive. A good agreement would not be expected, however, in view of the fact that the two areas are most frequently under the influence of entirely different atmospheric-dynamic systems. Mean monthly pressures at San Francisco and Honolulu were then compared but with the same results. In the latter case the departures were of the same sign in approximately the same number of cases as of opposite sign.

A comparison of mean monthly pressures at Mazatlan, Mexico (lat. 23° N.) and Honolulu (lat. 21° N.), however, indicated somewhat better correspondence. Even though the pressure departures at these stations were usually of small magnitude, it was interesting to discover that the departures were of similar sign in only twenty out of eighty months examined. The relationship was particularly outstanding during several seasons when the pressure departures at either station were particularly significant.

None of the data examined appear particularly conclusive from either point of view and the most that can be said is that local pressure departures do not imply significant departures of opposite sign within small areas where hydrostatic adjustments in sea level are possible. This fact is of little importance, however, since the total pressure departures are invariably small and not of the proper order of magnitude to account for the departures in sea level.

The evidence so far presented appears to indicate that the hydrostatic effects of pressure are relatively non-important. It must be concluded that the sea level departures that occur simultaneously with departures of atmospheric pressure are largely manifestations of significant meteorological changes over the ocean. Since no appreciable flow of surface waters can take place due to slopes produced through the hydrostatic deformation, it must be assumed that the meteorological effects are largely those of winds on ocean currents.

[1] Areas of plus departures and minus departures, respectively.

DYNAMICS OF THE ATMOSPHERE AS RELATED TO SEA LEVEL

Mean monthly wind data for the North Pacific are not available for detailed analyses of the effects of wind on ocean currents and sea level but it is possible to compute mean wind velocities for individual months from the pressure maps previously described. Winds thus computed from the pressure gradient are more consistent, easier to handle and probably as correct as those based on Beaufort estimates. This is particularly true when a few widely separated ships are available; it is possible to accurately define a pressure system with comparatively few reports but many reports are necessary to define the wind system with the same degree of accuracy.

Since neither wind velocity nor the resulting water transport due to these winds vary linearly with respect to pressure gradients, nor to one another, any close quantitative relationship between mean monthly pressure gradients and sea level would not be expected. Nevertheless, since the twenty maps have been prepared for months when sea level departures were greatest, it would be expected that the pressure departures would be equally outstanding and would thereby serve to give a qualitative picture of the major wind effects.

A cursory examination of these maps at once shows that sea level at the four tide stations is below normal when the high pressure field over the North Pacific is best developed or displaced toward the coast, and above normal when the system is weak or displaced toward the south or west. This relationship is particularly outstanding during the spring and summer months when the Pacific high pressure system is dominant and the short-period meteorological changes of small magnitude. The relationship is not always so apparent during the fall and winter months when the atmospheric-dynamic system is considerably more complicated. Three maps prepared for December months do not show this relationship between pressure and sea level to any degree but it may be remarked that the meteorological changes during the periods under consideration were so great and so rapid that it was impossible to construct reasonable mean pressure maps for these months.

Data regarding the pressure gradients measured between longitude 140° W. and San Francisco are given in Table I. It may be noted that the sign of the departure of pressure gradient differs from the sign of the departure of mean monthly pressure over the same area in only one case of the twenty (Feb. 1931). Thus, when the mean atmospheric pressure along the coast is high, the pressure gradient is relatively large; when pressures are low, the pressure gradients off the coast are small. The good agreement between the mean pressure at San Francisco and sea level illustrated in Figure 59 is immediately explained and the suggested condition (3), (p. 184) apparently satisfied.

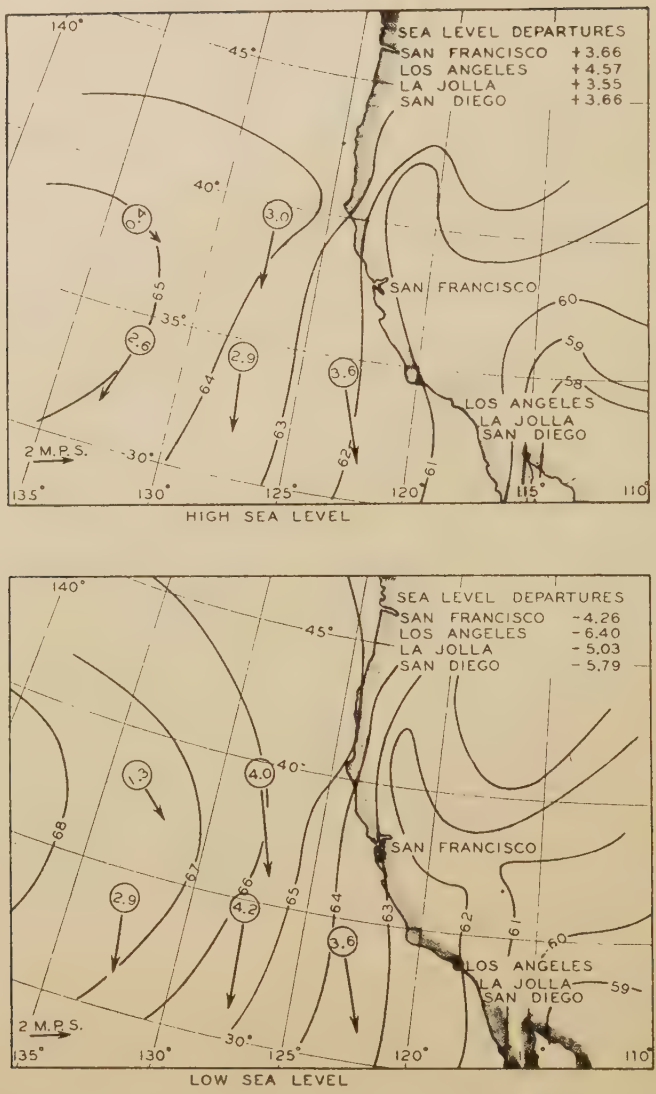

Figure 61. Composite maps of the pressure distribution over the Eastern North Pacific Ocean for periods of high sea level (above) and low sea level (below). The pressures are in millimeters; the sea level departures entered in the circles are in centimeters. The resultant northerly component of the wind in meters per second is entered in the circles on the wind arrows. Seasonal effects have been eliminated through the selection of data, i. e., an equal number of each of the calendar months appear in each of the maps.

Composite maps for all months with high and with low sea level are shown in Figure 61. Seasonal effects have been eliminated through the selection of data. These maps are typical of most of those in the series with the exceptions of the three months mentioned previously. The surface winds computed from the illustrated pressure fields parallel the coast in the cases of both maps but the map showing the lower sea level values at the four coastal stations presents the highest velocities. The surface winds computed on the basis of the pressure distribution have been multiplied by the factor 0.62 (Rossby, 1936) but this factor may be somewhat in error because

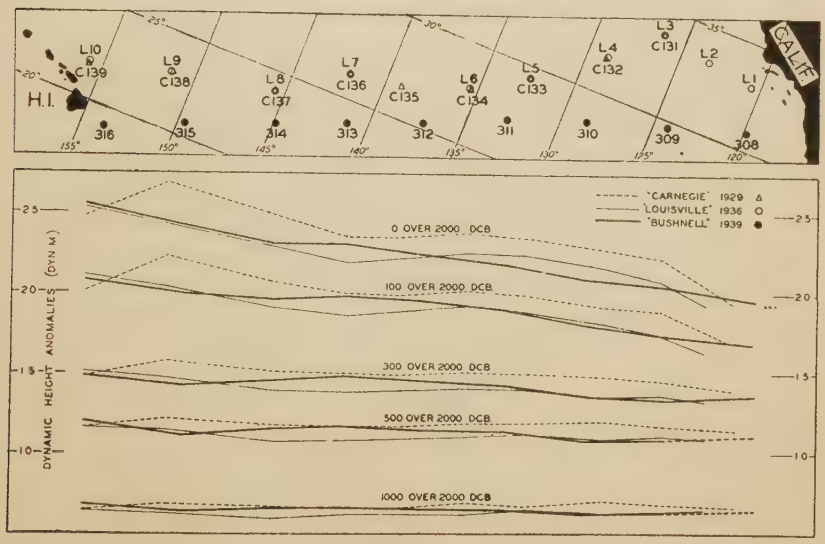

Figure 62. Dynamic heights over the Eastern North Pacific Ocean between longitude 131° W. and 139° W. computed on the basis of the *Carnegie*, *Louisville* and *Bushnell* sections.

of the great stability of the lower layers throughout nearly all months. This error will be most significant during the late spring and early summer months when the coastal inversion is best developed. However, at the present time no practical method of eliminating this difficulty is apparent.

Since the North Pacific high pressure system normally persists throughout all months, it would be expected that the sea surface would slope upward from the coast toward the center of the pressure field as a result of the *cum sole* transport of the surface waters induced by the anticyclonic wind system. The dynamic heights computed from the *Carnegie*, *Louisville* and *Bushnell* sections (Figure 62) show this to be the case, the rise of the surface being of the order of 30 cm. between 130° W. and 140° W. The short-period sea-

level fluctuations on the coast are occasionally of the order of 30 cm. or more although the monthly departures seldom exceed 8–12 cm.

The longer the period under consideration the more outstanding is the relationship between the development of the pressure field and sea level. This fact is in line with the conclusions drawn regarding local and widespread variations. For example, the entire year 1933 gave unusually low sea level at all tide stations on the Pacific Coast. Reference to data concerning mean annual pressures over the eastern North Pacific compiled by the Japan Imperial Marine Observatory (1934) reveals that the Pacific high pressure system was also unusually well developed during this year with a corresponding displacement of the pressure center toward the coast. The year 1930 on the other hand, gave unusually high sea level at the coastal stations. Reference to the same source of pressure data (loc. cit. 1931) reveals that the pressure system during this year was weaker than normal and displaced to the west. In addition, the area covered by the region of highest pressure was several times greater in 1933 than in 1930. In 1933 the central pressure was between 767 mm. and 768 mm. and the geographical center approximately located at latitude 31° N., longitude 139° W. In 1930 the central pressure was approximately one millimeter lower and the center was shifted to latitude 33° N., longitude 146° W.

The mean northerly wind component for the 1000 meter level at San Francisco was computed for several series of months on the basis of pilot balloon soundings.[1] The results gave a fair agreement between the component at this level and sea level departures during the spring and summer months but, as with other data, the agreement was not as good during the winter months. Previous investigation of the relationship between surface winds and sea level had given negative results for all months. However, it is well to bring out in this connection that the data are from soundings made once daily at 2:00 a. m. (P. S. T.) and thus at a period when surface winds are not often representative of the general circulation over the ocean due to the local effects of topography and the katabatic process. Figure 63 illustrates the relationship between the northerly component at 1000 meters and sea level departures at San Francisco for all months of April, 1929–36. The agreement between the two elements indicated in the diagram is probably as good as could reasonably be expected since the increased velocities due to changes in the pressure field over the North Pacific may appear at some distance from the coast and not be apparent at the coastal stations. The existence of such a condition off the coast of Southern California is indicated in Figure 61.

It has previously been mentioned that other investigators of the problem

[1] The greater portion of the soundings were actually made at Oakland, several miles inland from San Francisco.

have found most of the sea level variations accounted for by changes in the density of surface waters, but it should be pointed out that the changes in density can only be accounted for by meteorological processes, either directly or indirectly. The transport of light surface waters away from the coast will bring sub-surface waters of greater density to the coastal regions and the isopycnal surfaces will now slope upward toward the coast. LaFond (loc. cit.) has shown that the greatest change in density off the Southern

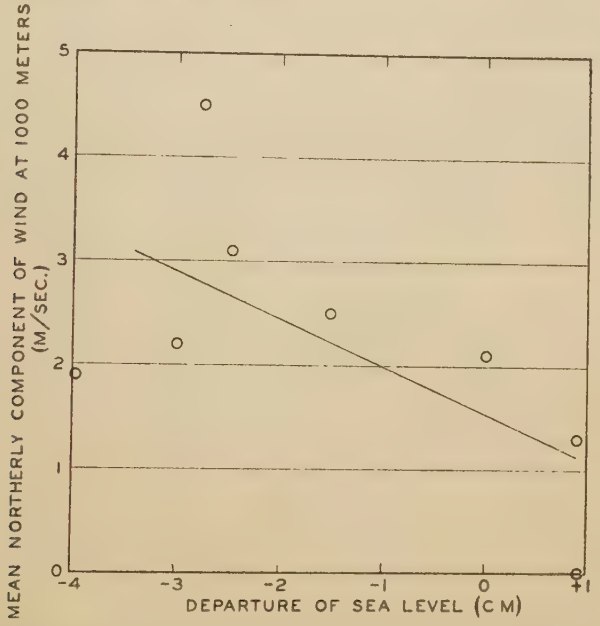

Figure 63. Relationship between sea level departures at San Francisco and the mean monthly northerly wind component at 1000 meters computed on the basis of pilot balloon soundings for all months of May, 1929–36.

California coast tends to occur in the upper 75 meters and that the changes in density below this level can account for only a fraction of the observed sea level departures. It is true that the intrusion of waters of greater density may occur as the result of subsurface currents but it may be assumed that these currents, too, are the result of the general circulation of surface waters.

Evaporation and precipitation may also alter the distribution of density, but none of these processes can directly influence sea level to any appreciable extent. Nevertheless, LaFond (loc. cit.) has shown a good agreement between the annual rainfall at La Jolla and the annual sea level departures.

It must be concluded that the meteorological processes causing precipitation in this region also produce high sea level and a consideration of the problem indicates that this is the case. Because the San Diego area is near the boundary region for winter cyclonic activity, seasons with above normal rainfall should also show a general shift of the Pacific high pressure field from the coast seaward and correspondingly, winds with a northerly component should be less frequent. A shift to the south of the high pressure field may actually bring the Southern California area within a zone of frontogenesis with resulting increase in precipitation.

In summation it may be stated that the current system produced by the wind is extremely complicated and at the present time not well understood. It is probable that *cum sole* transport of surface waters always takes place but is compensated for by vertical motion near the coast. A discussion of the total effects of the wind, however, entails consideration of thermodynamics as well as dynamics because the effect of heating and cooling of surface layers may counteract the effect of the wind and may limit the development of a pure wind circulation, which otherwise would be limited by frictional forces only. In light of the numerous difficulties involved and the meager data available for testing the conclusions, even a crude theoretical treatment of the general problem does not appear justified. Further investigation into the nature of the oceanic circulation off the Southern California coast which is anticipated by the Scripps Institution may render some such considerations possible in the future.

SUMMARY

1. The good agreement between departures in atmospheric pressure and departures in sea level at stations on the Pacific Coast is not explained by the hydrostatic effect of pressure difference.

2. It is shown that sea level averages for time intervals of one month or longer are definitely related to the development of the high pressure field over the North Pacific Ocean.

(a) Low sea level values occur when the pressure field is best developed or shifted toward the coast; high sea level is recorded when the system is weak or shifted toward the west or south.

(b) This relationship is most pronounced during the spring and summer months when the atmospheric-oceanic system is least complicated by local and short-period meteorological changes.

3. It is concluded that the effect of the pressure distribution is due to the wind system produced by the gradients established and that the total mass of water transported away from the coast varies as the wind component parallel to the coast. An agreement between the northerly component of the wind at 1000 meters and sea level is found.

4. It is suggested that the good agreement between the density of surface waters, rainfall and sea level found by various investigators may be explained on the basis of variations in the atmospheric-dynamic system over the regions under consideration.

Acknowledgements

The author desires to express his appreciation to Dr. H. U. Sverdrup for assistance and advice during the entire course of the investigation and at whose suggestion the present study was undertaken; to the San Diego Office of the U. S. Weather Bureau for furnishing meteorological information; to the U. S. Coast and Geodetic Survey for supplying the sea level data; and to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and the Hydrographic Office of the U. S. Navy for the use of unpublished oceanographic data used in the construction of the profiles in Figure 62.

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LATERAL MIXING IN THE DEEP WATER OF THE SOUTH ATLANTIC OCEAN*

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The deep-sea circulation of the Atlantic has recently been carefully analyzed by Wüst (1935) who, on the basis of the tongue-like distribution of temperature and salinity, has drawn conclusions as to the direction of flow at different depths. He considers that an exchange of deep water between the North Atlantic Ocean and the Antarctic Ocean is maintained by a flow to the north along the bottom of Antarctic water and a flow to the south at lesser depths of North Atlantic deep water and Mediterranean water.

The temperature and salinity sections from the Atlantic Ocean clearly show that the Antarctic bottom water loses its identity as it flows north since temperature and salinity both increase in the direction of flow and, similarly, that the North Atlantic deep water loses its identity as it flows south since temperature and salinity both decrease in the direction of flow. Defant (1936) has accounted for these changes by considering processes of mixing in a vertical direction. He has shown that the distribution of temperature and salinity may depend on the ratio between the velocity of the flow and the virtual coefficient of diffusion, and, in the case of the South Atlantic Ocean, he has computed the numerical values of this ratio which correspond to the observed distributions.

It has been assumed that the lateral coefficients of diffusion are of the same order of magnitude as the vertical and that the effect of lateral mixing is insignificant because of the small horizontal gradients, but in view of recent results it appears desirable to examine the correctness of these assumptions. Rossby and his collaborators have shown that in the atmosphere a large-scale quasi-horizontal isentropic mixing takes place and Rossby (1936) has suggested that such lateral mixing may take place in the ocean as well, where it should follow σ_t-surfaces. Parr (1938) has demonstrated the importance of such lateral mixing to the distribution of temperature and salinity off the Grand Banks of Newfoundland, and by means of as yet unpublished data off the coast of California R. H. Fleming and the author (Sverdrup and Fleming, in press) have found that there the lateral mixing is

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of dominating importance between depths of 200 and 400 meters, the coefficient having a numerical value of about $2 \times 10^6 \text{cm}^2\text{sec}^{-1}$. Seiwell (1938) has found that in the Caribbean Sea distribution of temperature and salinity will not be influenced by lateral mixing unless the coefficient is greater than 10^6, and Montgomery (1939) has shown that in the Equatorial Counter Current of the Atlantic the salinity distribution can be accounted for by introducing a coefficient of lateral mixing of $4 \times 10^7 \text{cm}^2\text{sec}^{-1}$ and neglecting the effect of vertical mixing.

It is evident that a lateral mixing of such intensity as that found off the coast of southern California or that suggested by Montgomery in the region of the Atlantic Equatorial Counter Current may be of importance to the general distribution of temperature and salinity, and our first question is, therefore, whether factors are active which can maintain an intensive lateral mixing at great depths. So far, evidence for the existence of lateral mixing has been obtained from coastal areas where the development of quasi-horizontal eddies may be ascribed to the effect of the solid boundaries, or from an area characterized by swift currents in opposite directions where eddies may develop along the boundaries of the currents. Rossby (1938) has, however, recently shown that changes of the winds over the ocean may produce currents reaching from the surface to the greatest depths. All such motion will be directed at random and Rossby's conclusion, therefore, can be interpreted as showing that changing wind conditions may produce variable currents in the deep water, but no flow in a definite direction. If this is the case, a large-scale lateral mixing may take place. In view of these conclusions, it appears worth while to examine to what extent processes of lateral mixing contribute towards maintaining the observed distribution of temperature and salinity in the deep sea.

In a two-dimensional system the general condition for a stationary distribution of a conservative property, s, is:

$$(1) \qquad \frac{\partial s}{\partial t} = \frac{\partial}{\partial l}\left(A_l \frac{\partial s}{\partial l}\right) + \frac{\partial}{\partial n}\left(A_n \frac{\partial s}{\partial n}\right) - u\frac{\partial s}{\partial x} - w\frac{\partial s}{\partial z} = 0$$

where u and w are the velocity components, and where A_l and A_n are the coefficients of lateral and vertical mixing expressed as coefficients of diffusion.

Equation (1) is far too complicated to form a basis for any study, but from this equation three others can be derived, introducing different assumptions as to the variables. Assuming $w = 0$, A_n and A_l to be constants, and the effect of lateral mixing to be negligible, one obtains

$$(2) \qquad A_n \frac{\partial^2 s}{\partial n^2} - u\frac{\partial s}{\partial x} = 0$$

Assuming $w = 0$, A_n and A_l to be constants and the effect of vertical mixing to be negligible, one obtains:

$$A_l \frac{\partial^2 s}{\partial l^2} - u \frac{\partial s}{\partial x} = 0 \tag{3}$$

Finally, assuming $w = 0$, $u = 0$, and A_n and A_l to be constants, one obtains

$$A_l \frac{\partial^2 s}{\partial l^2} + A_n \frac{\partial^2 s}{\partial n^2} = 0 \tag{4}$$

Defant (1936) has used equation (2) in a modified form which takes into account the fact that the deep-sea currents need not be strictly horizontal and has computed values of A/u in the deep and bottom water of the Atlantic Ocean and in the Antarctic intermediate water. In his study of the Equatorial Counter Current of the Atlantic Ocean, Montgomery (1939) has used the equivalents of equation (2) and (3) which apply to a three-dimensional system, and in their discussion of conditions off the coast of southern California Sverdrup and Fleming (in press) used the same equations. Equation (4) has so far not been made use of.

It is of interest, in the first place, to observe that equations (2) and (4) have some common integrals. Thus, one of the tongue-like distributions discussed by Defant (1929) satisfies (2) and is represented by

$$s = s_0 + \delta e^{-\alpha x} \cos \pi \frac{z}{2l}$$

where

$$\alpha = \frac{\pi^2}{4l^2} \frac{A_z}{u}$$

The same distribution also satisfies (3) if

$$\alpha = \frac{\pi}{2l} \sqrt{\frac{A_x}{A_z}}$$

The two solutions are identical if

$$\frac{A_x}{A_z} = \left(\frac{u}{A_z}\right)^2 \frac{4l^2}{\pi^2}$$

In a numerical example Defant introduces $l = 300$ m $= 3 \times 10^4$cm and $A/u = 20$. With these values one obtains

$$A_x = 0.9 \times 10^6 A_z$$

Defant's numerical values were selected in order to represent a tongue-like distribution of salinity of dimensions corresponding to those encoun-

tered in the ocean. It is of interest to observe that the same distribution can be explained as a result of processes of mixing alone provided that the ratio between the vertical and lateral coefficients of diffusion is about 10^6 which is the ratio found off the coast of California. Thus, tongue-like distributions may result from horizontal flow and vertical mixing or from processes of mixing only.

Another solution of equation (3) can be written

$$s = s_0 + \delta \frac{\cos h\,[\beta(h - z)]}{\cos h\,[\beta\, h]} \sin \pi \frac{x}{2l}$$

provided that

$$\frac{A_x}{A_z} = \frac{4l^2}{\pi^2} \beta^2$$

Placing the z-axis vertically downwards and considering the distribution of the property within the interval $0 < z < h$ and $0 < x < 2l$ one obtains curves which have a slight similarity to isotherms in a vertical north-south section through an ocean and the author (Sverdrup, 1939) therefore suggested that the distribution of deep-sea temperature might result from processes of mixing only.

A closer examination of the distribution of temperature and salinity in the South Atlantic Ocean has now been completed, but this has clearly shown that the above suggestion is not correct as far as conditions in that ocean are concerned. The results do indicate, however, that in general the processes of lateral mixing are of greater importance than those of vertical mixing.

The examination was based on the horizontal charts of temperature and salinity by Wüst (Wüst and Defant, 1936). The selected area extends between latitudes 60° and 30° S. and from the South Atlantic Ridge to the South American Continent and the South Antillean Arc. The eastern boundary passes through the points 30° S., 15° W., 40° S., 15° W. and 60° S., 10° E. In this area average values of temperature and salinity were computed along every 5° of latitude at the depths 2000 m., 2500 m., 3000 m., 3500 m., and 4000 m. The average values were used for constructing vertical and horizontal curves by means of which the smooth isotherms and isohalines in Figures 64 and 65 were plotted. The following discussion will deal only with conditions between 2500 m. and 4000 m. within which interval of depth the corresponding average values of σ_t vary only between 27.80 and 27.87. The σ_t curves 27.82 and 27.84 have been plotted in Figure 64.

A further study of these vertical sections which represent average conditions in the western part of the South Atlantic Ocean may be criticized on the basis that by the process of averaging, the characteristic details are removed. It may particularly be pointed out that the tongue of cold water

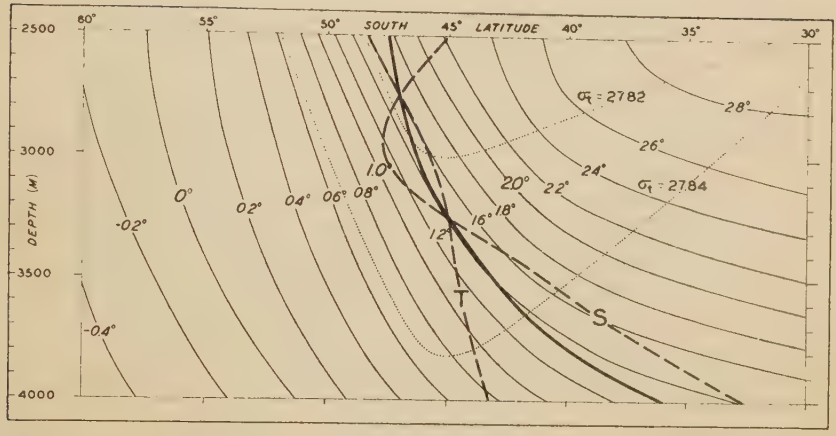

Figure 64. Average distribution of temperature in the South Atlantic Ocean between latitudes 60° and 30° S. and between depths of 2500 and 4000 meters, based on Wüst's horizontal charts. Lines marked T and S represent the boundaries between flow to the north and flow to the south as derived from temperature and salinity, respectively.

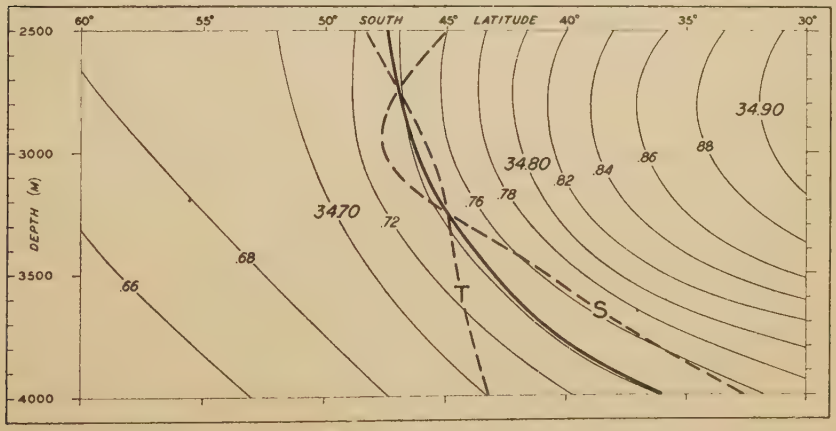

Figure 65. Average distribution of salinity in the South Atlantic Ocean between latitudes 60° and 30° S. and between depths of 2500 and 4000 meters, based on Wüst's horizontal charts. Lines marked T and S represent the boundaries between flow to the north and flow to the south as derived from temperature and salinity, respectively.

of low salinity along the coast of South America ought to be considered as a separate phenomenon. It can be emphasized on the other hand that a comparison between our sections and those prepared by Wüst (1935) on the basis of individual stations all show similar features and our sections there-

fore give a representation of the general distribution of temperature and salinity in a south-north direction in the South Atlantic.

Our problem is now to examine the character of the processes which can maintain stationary the distributions of temperature and salinity shown in Figures 64 and 65. This problem can be simplified by asking if the average distribution of temperature and salinity satisfies one or more of the equations (2), (3), and (4) in which A_n and A_l are positive constants and in which a positive value of u indicates flow to the north and a negative value indicates flow to the south. Applying equations (2) and (3) the ratios A_n/u or A_l/u, as derived from temperature and salinity distribution, must agree both as to sign and as to numerical value, and applying equation (4) the ratio A_l/A_u must always be positive and the values must agree numerically whether derived from temperatures or from salinities.

In order to compute the different ratios the derivatives

$$\frac{\partial s}{\partial l}, \frac{\partial^2 s}{\partial l^2} \text{ and } \frac{\partial^2 s}{\partial n^2}$$

must be found. For this purpose it should be known whether the flow is horizontal and whether the lateral mixing takes place in a horizontal direction. It will be assumed that in the first approximation horizontal and vertical coordinates can be used because the variations in σ_t are very small. The different derivatives have therefore been computed along vertical and horizontal lines and from these the ratios A_x/A_z, A_z/u and A_x/u have been computed by means of equations (4), (2) and (3), respectively. The results are summarized in Tables I, II, and III.

TABLE I

VALUES OF $10^{-5}A_x/Az$

a. From temperature

Depth	*South latitude*						
m	*60°*	*55°*	*50°*	*45°*	*40°*	*35°*	*30°*
2500	?	−7	−6	−7	−8	−30	−71
3000	?	?	−8	3	−11	−25	−230
3500	?	6	11	−60	7	1	−89
4000	?	6	31	?	7	?	−15

b. From salinity

2500	−41	−8	−16	12	−48	−36	−42
3000	95	12	10	−195	−66	−67	−47
3500	−78	−22	−8	−25	?	−45	−27
4000	−40	−50	17	−100	−74	−230	200

Table I contains the values of $10^{-5}A_x/A_z$. If this ratio shall have any physical significance it must, as already stated, be positive because A_x and A_z are both positive constants. It is seen, however, that the ratio is mainly *negative* from which it follows that processes of mixing alone can not account for the observed distribution of temperature and salinity in the area under consideration.

Table II contains the values of the ratio A_z/u. The coordinates are selected in such manner that a positive sign corresponds to flow towards the north and a negative sign corresponds to flow towards the south. In many instances it was not possible to determine this ratio, particularly because

TABLE II

VALUES OF A_z/u

a. From temperature

Depth	*South Latitude*						
m	*60°*	*55°*	*50°*	*45°*	*40°*	*35°*	*30°*
2500	?	150	420	−100	−76	−10	−8
3000	?	?	80	450	−34	−16	−2
3500	?	−220	−180	340	120	?	−24
4000	?	−170	−70	?	110	?	−120

b. From salinity

2500	6	75	75	−330	−50	−60	−35
3000	−6	−32	−70	−34	−39	−31	−26
3500	23	50	120	39	?	−25	−27
4000	84	65	−160	29	38	14	15

the vertical second derivative of temperature was too small. From the table it is seen that both the magnitude and the sign of the ratio vary irregularly and that no consistency exists between results derived from the temperature and from the salinity distribution except between latitudes 40° and 30° S. This area overlaps a small portion of the area which was examined by Defant (1936), and the distribution of the sign of the ratio corresponds to that found by Defant, but our values are three or four times larger than his. His examination was, however, based on different data and a complete agreement can therefore not be expected. The main point is that in the larger part of the section under consideration the distribution of temperature and salinity can not be accounted for as resulting from vertical mixing and horizontal flow, but in the northern portion of the section these processes may be of importance.

Table III contains the values of $10^{-7}A_z/u$ as derived from temperature and salinity, and the bottom portion of the table gives the averages. In this case there is a remarkable regularity in the variation of the sign and in the numerical values. On the whole, there is a good agreement between results derived from temperature distribution and from salinity distribution. Positive values indicating flow to the north are found in the southern part

TABLE III

VALUES OF $10^{-7}A_z/u$

a. From temperature

Depth	*South latitude*						
m	*60°*	*55°*	*50°*	*45°*	*40°*	*35°*	*30°*
2500	12	5	?	−7	−6	−3	−6
3000	8	13	7	−13	−4	−4	−6
3500	10	15	20	?	−8	−9	−19
4000	4	11	22	34	?	−10	−18

b. From salinity

2500	2	6	12	?	−24	−21	−15
3000	6	4	7	?	−26	−20	−12
3500	18	11	9	10	?	−11	−7
4000	34	32	26	29	29	?	−29

c. Averages

2500	6	6	?	?	−15	−12	−10
3000	7	8	7	?	−15	−12	−9
3500	14	13	14	?	?	−10	−13
4000	19	22	24	32	?	?	−24

of the section and the horizontal distance to which this flow reaches increases with increasing depth. The numerical values obtained from temperature and salinity are in fair agreement. In the northern part of the section all values are negative, indicating flow to the south, and in this case the extent of the flow to the south decreases with increasing depth. Thus, the distribution of temperature and salinity can be accounted for if horizontal mixing dominates and if in the southern portion of the section the flow is directed to the north and in the northern portion of the section to the south, the two currents being separated by a boundary surface which slopes downward from south to north. In Figures 64 and 65 are entered the

boundaries between the flow to the north and the flow to the south as derived from temperature and salinity data. The lines do not quite coincide, for which reason an average line has been plotted.

The good agreement within the flow to the north of the values of A_z/u derived from temperatures and from salinities indicates perhaps that there the flow is nearly horizontal. Within the flow to the south the ratios derived from the temperature distribution are, however, much smaller than those derived from the salinity distribution, which may indicate that there the flow is not horizontal. An examination of the sections in Figures 64 and 65 shows that the ratios can be brought into better agreement by assuming descending motion. Within this flow significant differences in density are found as seen from the σ_t curves which are entered in Figure 65. If it is assumed that both the current and the lateral mixing are directed along σ_t surfaces the values of A_z/u derived independently from the temperature and salinity distributions are actually brought into agreement and are both about 8×10^7, that means somewhat smaller than the averages in the bottom part of Table III.

The above results demonstrate that in the section under discussion the distribution of temperature and salinity can be completely accounted for by nearly horizontal flow which is directed to the north in the southern part, and to the south in the northern part, and by processes of lateral mixing which in the southern part, where uniform density distribution is encountered, is horizontal, but in the northern part follows σ_t surfaces. If the velocity of the currents is about 1 cm/sec the coefficient of lateral mixing will be about 10×10^7 or twice as large as the maximum value found by Montgomery in the Equatorial region. Within both currents the velocity decreases with depth if the coefficient of lateral mixing can be considered constant.

It was pointed out that north of latitude 40° S. the vertical mixing may be of importance because the ratio A_z/u was consistent. This result is perhaps significant. If the lateral mixing is maintained by the effect of variable winds one must expect the lateral mixing to be most intense in the regions of variable wind systems, but less important over areas of constant wind conditions. In the southern part of the South Atlantic Ocean strong and variable winds dominate but in the central part lower wind velocities and less variable conditions are encountered, such that for these reasons a decrease of the intensity of the lateral mixing from south to north may occur.

It is not surprising that the coefficient of lateral mixing appears to be about 100 times greater than that off southern California. There a small area was examined within which the eddies associated with the lateral mixing were of dimensions 10 to 20 km. Here a large part of the open ocean is considered and the dimensions of the eddies are probably several hundred

kilometers. The lateral mixing dealt with here probably corresponds to the macro-turbulence of the atmosphere.

The boundary surface between the deep currents to the north and to the south represents a region of convergence. The south-flowing Atlantic deep water must rise towards the surface in this region and the same is true as far as the greater amount of the north-flowing Antarctic water is concerned. This water can not sink under the south-flowing water because this would lead to bottom currents of unreasonable velocities. One is therefore forced to conclude that both the Antarctic water and the Atlantic deep water rise along the boundary surface separating two currents and that the water

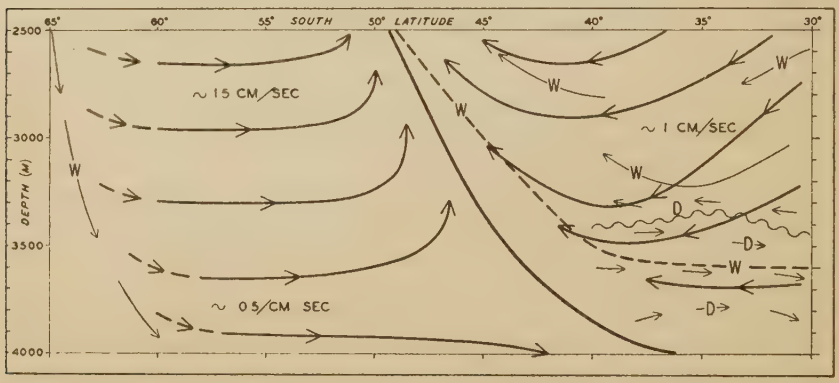

Figure 66. Meridional circulation in the South Atlantic Ocean derived on the assumption that the average distributions of temperature and salinity are maintained stationary by meridional flow and lateral mixing. Thin lines marked *W* represent the corresponding circulation according to Wüst (1935), and dashed line marked *W* represents the boundary between flow to the north and flow to the south according to Wüst. Small arrows marked *D* and wavy line marked *D* represent flow and boundary according to Defant (1936).

which ascends between latitudes 45° and 50° S. is formed by mixing of the two types. This conclusion is in agreement with the fact that the ascending water actually is intermediate in character between that of the two opposing types. This analysis therefore leads to an amplification of the picture of the deep-sea currents of the South Atlantic which has been prepared by Wüst (1935). Figure 66 gives a schematic representation of the deep-water flow based upon the present analysis, and in the same figure are entered the arrows which are shown in the same area by Wüst and the boundary surface which Wüst has determined between the Atlantic deep water and the Antarctic bottom water. The agreement is good except in the northern part where Wüst places the boundary surface higher than according to our results. In the figure is also shown Defant's boundary surface between the Atlantic deep water and the bottom water, and small arrows indicating his

computed directions of flow. Defant's boundary surface also falls somewhat above the one determined here. Our analysis shows, in addition to these features, that the Antarctic deep water flows north between latitudes 60° and 50° S. and contributes to the ascending motion between latitudes 50° and 45° S.

The order of magnitude of the ascending motion is about 10^{-2} cm/sec or 10 m. per day, if it is assumed that the ascending motion takes place over a 500-km. wide area and that the velocities of meeting deep currents are about 1 cm/sec. An ascending motion of 10 m. per day appears large and it is therefore possible that the current velocities are less than 1 cm/sec. Wattenberg (1938) has pointed out, however, that south of latitude 50° S. one must assume a considerable ascending motion of the deep water in order to account for the high phosphate content of the surface waters during the period of the year when an enormous phytoplankton production takes place. The present picture is, therefore, in fair agreement with all of the available information.

In conclusion it should be emphasized that the above analysis should be considered as a first attempt to show that processes of lateral mixing must be taken into account when drawing conclusions as to currents in the deep-sea based on the distribution of properties. The results give added weight to the concept that large-scale lateral mixing takes place, but it should be admitted that many more data are needed for an examination which can lead to a final picture of the processes which are operating.

SUMMARY

1. The importance of lateral mixing in maintaining the distribution of temperature and salinity is discussed.

2. In the case of a two-dimensional system the general equation of stationary conditions is broken down into three separate equations, one by means of which the ratio A_z/u (A_z, coefficient of vertical mixing, u, horizontal velocity) can be computed if the distribution of properties is maintained by horizontal flow and vertical mixing, one by means of which the ratio A_x/u (A_x, coefficient of lateral mixing) can be computed if the distribution is maintained by horizontal flow and lateral mixing, and one by means of which the ratio A_x/A_z can be computed if the distribution is maintained by processes of mixing only.

3. Sections of average temperature and salinity distribution in the western South Atlantic Ocean between 60° and 30° S. were derived from the horizontal charts by Wüst and Defant, and the three ratios A_z/u, A_x/u, and A_x/A_z were computed.

4. It was found that only the ratio A_x/u showed consistent values over the entire section. It was concluded that between 2500 and 4000 m. Antarc-

tic deep water flows north, the flow reaching to about 50° S. at 2500 m. and to about 40° S. at 4000 m. The Atlantic deep water, on the other hand, flows south, the flow reaching to about 40° S. at 2500 m. and to about 35° S. at 4000 m. Between the two currents is an area of convergence, which slopes downward from south to north.

5. The distribution of temperature and salinity can be accounted for as a result of these currents and processes of lateral mixing which in the uniform Antarctic deep water are horizontal but in the Atlantic deep water are directed along σ_t surfaces. If the average current velocities are about 1 cm/sec the coefficient of lateral mixing is about $10^8 cm^2 sec^{-1}$. The ascending velocity in the area of convergence is about 10 m. per day and the ascending water represents a mixture of Antarctic deep water and Atlantic deep water. In the northern part of the area vertical mixing may be of importance as shown by Defant. The results amplify those by Defant and Wüst and the conclusions are generally in agreement with their findings.

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INVESTIGATIONS ON THE MICROBIOLOGY OF MARINE AIR

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All the viable microorganisms in the air have been transferred to the atmosphere either from the land or the sea. A comparison of the micro-flora of marine air with that of normal sea water and of land areas should indicate the major source of organisms in the atmosphere over the ocean.

There have been few attempts to determine the origin of the bacteria occurring in marine air. Fischer (1886) assumed all the bacteria in the air came from the land, and concluded that under normal conditions the ocean air is nearly germ free 120 miles from shore. ZoBell and Mathews (1936) found both marine and land bacteria in the air over the ocean, and distinguished between them on the basis of growth on different types of media. The investigations of Levin (1899), Gazert (1902, 1903), Hesse (1913), Pirie (1913), and others were mainly concerned in showing the presence or absence of bacteria in the air over certain marine locations and have little direct bearing on this paper.

EXPERIMENTAL

The field investigations were carried out on board the research vessel *E. W. Scripps*, in an area off the Pacific Coast ranging from Cedros Island to Monterey, and from the mainland to 400 miles at sea. The observations were made during a series of cruises in 1938 and 1939, and so the stations occupied were widely separated in both location and time. A board frame constructed to hold nine Petri dishes, was attached to the crosstree of the mainmast sixty-five feet above the deck. The section of the frame holding the dishes projected out about three feet from the crosstree, and was clear of all the rigging. The board was so oriented that when the boat hove to on location the wind blew across it into the rigging, thus avoiding contamination from the ship.

According to ZoBell and Feltham (1933) most marine bacteria cannot grow in fresh-water medium while most terrigenous forms fail to multiply

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TABLE I: Number of Bacteria and Molds Developing on Plates Exposed to Marine Air

Station	*Date and location*	*Nearest land in nautical miles*	*Wind direction and force (Beaufort scale)*	*Minutes exposed*	*Sea-water medium*		*Tap-water medium*	
					Bacteria	*Molds*	*Bacteria*	*Molds*
FPS 229	9/20/38 121° 47.9′ W. 36° 48.2′ N.	0.5	calm	15	51 79 36 89	59 51 95 58	23 28 17 15	61 98 47 34
FPS 258	9/30/38 120° 2.5′ W. 34° 14′ N.	15	NW. 2	10	5 3 3 3	44 65 60 41	3 1 3 2	44 64 71 87
FPS 187	8/3/38 119° 37′ W. 32° 23′ N.	110	NW. 2	60	2 0 0 8	4 4 3 2	2 0 2 2	5 5 5 2
EWS 21	12/13/38 120° 12′ W. 32° 33.5′ N.	110	ESE. 3	5	79 16 23 7	1 3 5 5	1 0 3 0	3 12 6 4
F 78A	7/4/39 120° 10′ W. 26° 18′ N.	360	NW. 2	15	75 19 210	21 9 15	96 14 37	1 4 51

in sea-water medium. Since both types of organisms were expected, part of the nutrient medium used (0.3% peptone, 0.2% proteose-peptone, 0.2% beef extract, 0.0025% $FeCl_3 \cdot 6H_2O$, 1.5% agar) was made up with fresh-water and part with sea water. 10 to 15 cc. of medium were poured into Petri dishes and allowed to harden. The dishes were then stored in sterile cans until exposed. When the boat stopped on a station, four dishes containing sea-water medium and four containing tap-water medium were placed in the frame on the mast. The covers were removed and the plates exposed to the air for a period varying between five minutes and two and a half hours. A ninth plate was placed in the frame without removing its lid. It served as a control to indicate if contaminants were picked up during transport, manipulation, and storage. The direction and force of the wind during exposure was recorded as was the longitude and latitude of the station. After removal from the mast, the plates were incubated until returning to the laboratory where the colonies that developed were enumerated. The number of bacteria and molds were counted separately. The yeast were included with the bacteria since they could not always be distinguished by their colony characteristics alone. Their abundance was later estimated on the basis of a microscopic examination of a representative number of colonies.

Table I shows the field data from five typical stations. In most cases the counts on all plates of the same medium exposed at a given station were of the same order of magnitude, showing the microorganisms were usually uniformly distributed over a small area. At station F 78A, however, dishes exposed simultaneously at a distance not greater than a foot apart gave results as divergent as 210 and 19 bacteria and 51 and 1 mold per plate. This lack of uniformity introduces difficulties in interpreting the data obtained. The large and consistent differences between the number of bacterial colonies developing on the sea-water and tap-water media at station FPS 229 leads one to conclude that most of the bacteria in the air at that location originated from the ocean. A comparison of the average values at station F 78A of 101 bacteria per sea-water plate and 49 per tap-water plate would give the same conclusion. On the other hand examination of the results on individual plates reveals that the variation between counts on the same medium is greater than the difference between those on the two types of media. Instead of postulating a majority of marine bacteria one could ascribe the higher average of the sea-water plates to a fortuitous distribution of microorganisms in the air.

Table II gives the average colony counts calculated on an hour exposure time obtained at twenty-five different locations. The stations are arranged in order of increasing distance from land. The wind directions are given in relation to the position of the nearest shore, blowing over the ocean to the land during an onshore breeze and the reverse during an offshore wind.

TABLE II

AVERAGE NUMBER OF MICROORGANISMS DEVELOPING ON PLATES PER HOUR EXPOSURE

Station	*Nearest land in nautical miles*	*Sea-water medium*		*Tap-water medium*		*Wind direction*
		Bacteria	*Molds*	*Bacteria*	*Molds*	
FPS 228	0.5	4	36	7	55	onshore
FPS 229	0.5	255	263	83	240	calm
FPS 235	3.5	20	25	12	34	onshore
FPS 202	5.0	8	5	2	6	offshore
FPS 237	6.0	24	132	23	441	offshore
FPS 246	6.0	17	30	19	54	calm
FPS 242	7.0	23	424	12	730	offshore
FPS 243	9.0	6	5	2	42	offshore
FPS 258	13	14	489	14	400	onshore
EWS 18A	68	0	9	0	6	offshore
EWS 9A	75	18	39	3	48	onshore
EWS 9	91	17	42	9	50	onshore
EWS 6	93	36	72	9	57	onshore
FPS 190	105	2	12	5	8	calm
FPS 180	107	11	3	66	4	calm
FPS 187	110	3	3	2	4	onshore
EWS 21	110	375	42	12	75	offshore
EWS 22	125	3	78	8	40	offshore
EWS 24	165	broken	broken	60	90	offshore
FPS 182	215	6	9	3	39	onshore
FPS 185	230	2	18	3	12	onshore
FPS 185A	230	0	9	3	10	onshore
FPS 186	240	1	23	3	22	onshore
F 78A	360	404	60	196	75	onshore
F 77	380	13	0	4	3	onshore

The air was not completely free of microorganisms at any station. On several plates there was no development at all but others in the same series showed either bacteria or molds or both. Even four hundred miles out at sea there was an abundant micro-flora, and the largest bacterial population was found at F 78A, 360 miles from shore. The large variability of results from station to station is to be expected as we are not dealing with a single air mass; certain regularities in the distribution, however, become apparent on further analysis of the data.

At fourteen stations the average number of bacterial colonies developing on sea-water medium was greater than the number on tap-water medium,

while the opposite was true at eight stations. Only at five stations was the variation between plates of different media greater than that between plates of the same medium. In three of these the sea-water count was greater, in two the tap-water. This would indicate that either the number of marine and land bacteria were about the same or else that the organisms in the air could develop on both types of media. In order to further clarify this point 168 colonies were picked directly from the original sea-water plates and transferred to tap-water slants while 96 colonies were taken from tap-water plates to sea-water slants. 130, or 77 per cent of the former, and 69, or 72 per cent of the latter, developed. Accepting as marine bacteria those that do not grow on tap-water media, then less than 25 per cent of the viable bacteria in the marine air originated from the sea.

TABLE III

Relation Between Number of Microorganisms and Distance from Land

Distance from land in nautical miles	*Average number of colonies per hour exposure*			
	Sea-water medium		*Tap-water medium*	
	Bacteria	*Molds*	*Bacteria*	*Molds*
0–10	45	115	20	200
10–150	48	79	13	69
150–400	71	20	39	36

The number of molds developing on tap-water was greater at 16 stations and less at 8 than those developing on sea-water medium. In only two cases was the variation between media greater than the variation between plates of the same medium. 100 transfers were made from sea-water plates to tap-water slants. 97 of these cultures developed, and if anything, grew better on tap-water medium than on sea-water medium. The relative rate of growth on the two media was estimated by measuring the diameters of three hundred colonies developing on plates exposed at stations FPS 185 and FPS 185A. After the same period of growth an average colony diameter of 5.8 mm. on the tap-water medium and 2.3 mm. on the sea-water medium was found. These results strongly indicate the terrigenous origin of all the molds.

If most of the organisms in the ocean air originated from land sources we might expect to find a regular decrease in their numbers as we go farther away from shore provided we remain in the same air mass. Since our observations were separated by long intervals of distance and time the data does not represent a homogeneous air mass, but even so it was hoped that combining all results would bring out certain trends.

Table III was obtained by averaging all the results between given distance intervals from land. These intervals were arbitrarily chosen so as to include approximately equal amounts of data in each division.

The decrease in number of molds with distance from shore is quite apparent confirming our conclusion as to their land origin. The same relation does not appear to exist for the bacteria. This lack of a regular decrease might be explained in several ways. An examination of Table II shows three stations whose bacterial count on sea-water medium is much higher than the rest. Because of the small amount of data these high counts dominate the averages and may mask any relation that does exist. If we assume that these three results represent abnormal conditions in the atmosphere and omit them from our calculations, we obtain 15 as the average

TABLE IV

Relation Between Number of Microorganisms and Wind Direction

Wind direction	*Average number of colonies per hour exposure*				*Ratio of sea-water to tap-water counts*	
	Sea-water medium		*Tap-water medium*			
	Bacteria	*Molds*	*Bacteria*	*Molds*	*Bacteria*	*Molds*
offshore	63	99	17	204	3.70	0.49
onshore	41	63	21	63	1.95	1.00
calm	71	77	43	77	1.65	1.00

number of colonies developing per plate per hour exposure between 0–10 miles at sea, 11 between 10–150 miles, and 4 between 150–400 miles, showing a decrease with distance from shore.

On the other hand we can assume a significant number of organisms are carried into the atmosphere from the surface ocean water. This number would depend on the population of the water and the amount of agitation and would have no relation to the distance from land except in the narrow tidal zone where breaking waves send large amounts of spray into the air. The counts being the sum of a variable number of bacteria originating from the ocean and a constantly decreasing amount from land, would not be a function of the distance from shore. For reasons discussed below it is believed that the number of viable marine bacteria in the air is small so this latter explanation is only of minor significance.

The life history of an air mass should influence the number and type of organisms it contains. The number of bacteria in sea water is usually less than 500 per cc. (ZoBell and Feltham, 1934; Benecke, 1933) which is quite small compared to what is found in soil, dust, and other terrigenous surfaces.

Thus air traveling over the ocean for a long distance should contain fewer organisms and have a higher proportion of marine bacteria than air coming from the land. ZoBell and Mathews (1936) found a much higher ratio of marine to land bacteria during onshore winds than during offshore winds. They were working in the tidal zone where due to the large amount of spray in the air, a change in wind direction would have an almost immediate effect on the types of organisms found. It must be pointed out, however, that the wind direction at a given location does not necessarily indicate the life history of the air mass.

Table IV, which averages the results of all stations having similar wind directions, bears this out. Although the total number of organisms found during offshore winds was somewhat higher than during onshore winds, the ratio of sea-water to tap-water bacterial counts was also higher during offshore winds.

The morphological, biochemical and physiological properties of 100 cultures picked at random from sea- and tap-water plates were determined. 32 of this group were yeast, 30 cocci, 15 gram-negative rods and 23 gram-positive spore-forming rods. Fifteen different species listed below were identified by comparison with the characteristics given by Bergey (1939).

Bacillus subtilis
Bacillus flavus
Bacillus megatherium
Bacillus mycoides
Bacillus tumescens
Bacillus cohaerens
Bacillus laterosporus
Flavobacterium aquatilis
Achromobacter liquifaciens
Staphylococcus aureus
Staphylococcus albus
Staphylococcus citreus
Micrococcus flavus
Micrococcus candidus
Sarcina flava

This group shows a surprising resemblance to those found by Proctor (1934, 1935) and Proctor and Parker (1938) in the upper atmosphere. The following sentences quoted directly from Proctor's paper (1934) apply equally well to the entire group of cultures studied in this investigation. "Every species identified was found to be one which is commonly found in the soil, water, or air . . . It is interesting to note that no pathogens were found. Neither *Escherichia coli*, or similar intestinal types were found . . . None of these cultures have the ability to ferment common sugars with the formation of gas."

Another group of 120 colonies from stations F 77 and F 78A were stained and their morphology determined. There were two yeasts, 12 cocci, and 32 gram-negative rods. The remainder were gram-positive rods, most of which showed spores.

One hundred typical mold colonies were isolated and given to Dr. O. A.

Plunkett, and Mr. Kilpatrick, of the Department of Botany, University of California at Los Angeles, for identification. Most of them proved to be forms commonly found in the soil and none showed any characteristics which would indicate a marine origin. The following is a list of the genera found together with the number of times each genus occurred.

Actinomycete	2	Macrosporium	2
Alternaria	6	Pennicillium	18
Aspergillus	2	Penozythia	1
Cantenularia	1	Spicaria or Paecilomyces	1
Cephalosporium	7	Sporotrichium	7
Cladosporium	7	Stemphylium	3
Helminthosporium	1	Trichoderma	1
Hormodendron	15		

DISCUSSION

The micro-floras of sea water and marine sediments have certain characteristics which distinguish them from the populations of other natural environments. Fischer (1894) in the first comprehensive survey of marine bacteria remarked on the scarcity of molds in ocean waters. He found yeast in several samples but not in great abundance. Cocci and members of the genus *Bacillus* were almost entirely absent. Gazert (1912) and Hesse (1913) also found an almost complete lack of cocci and spore-forming organisms. ZoBell and Feltham (1934) found that about 90 per cent of the marine bacteria were gram-negative and less than 5 per cent were cocci.

This is quite different from what is found in marine air. Molds represented over 50 per cent of the population even on a medium not especially adapted to their needs. Yeasts constituted 15 per cent, cocci 19 per cent, gram-negative rods 21 per cent, and gram-positive rods 45 per cent of the remaining organisms.

A comparison of these two types of populations shows that land forms predominate in the air over the area studied. The great abundance of spore-forming organisms, both bacteria and molds, might be explained on the basis of their greater ability to survive adverse conditions. The presence of large numbers of these bacteria 400 miles from shore reveals the possibility of long distant transport of microorganisms through the atmosphere. The qualitative differences between the ocean and air micro-flora also shows that most of the organisms settling from the air into the ocean do not develop.

Although this work has been presented from a biological viewpoint there are unexplored possibilities of solving problems in other fields. At the present time there does not seem to be any property of an air mass which can serve to identify its source and history. It may be that an intensive

study of the types and sources of organisms in the air may serve as a tool in tracing the life history of air masses and in understanding the mixing processes they undergo (see the following paper by Jacobs).

SUMMARY

The microorganisms in the air over an area of the Pacific Ocean were studied by exposing nutrient media to the atmosphere. The average numbers of bacteria and molds developing on sea-water and tap-water medium were determined at 25 different stations.

The air was not completely free of organisms at any station. The numbers found varied greatly in different plates at a given station, and from station to station, but there appeared to be a general decrease in numbers with distance from shore.

Molds were the predominant group of organisms and spore-forming bacteria were next. Fifteen species of bacteria and the same number of mold genera were identified. The differences between the ocean and the air micro-flora indicates the terrestrial origin of most of the organisms.

The possible use of these investigations in solving meteorological problems is mentioned.

Acknowledgements

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A DISCUSSION OF PHYSICAL FACTORS GOVERNING THE DISTRIBUTION OF MICROORGANISMS IN THE ATMOSPHERE

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The preceding paper by Rittenberg, together with the number of articles on the same subject which have appeared recently, indicate an ever increasing interest on the part of biologists in the atmosphere as a medium for the dispersal of bacteria, molds, spores and pollens. Meteorologists, on the other hand, are interested in the results of such biological investigation to the extent that they show certain mixing processes within the atmosphere and the movements of air masses. In view of the large quantity of data which has already been accumulated by the biologists, it becomes of considerable interest to consider some of the results from the standpoint of fluid mechanics.

All investigations point to the fact that the atmosphere contains viable organisms at all times, even at free air elevations of eighteen to twenty thousand feet (Proctor 1934, 1935) indicating that large numbers of organisms are able to withstand the adverse gaseous environment for considerable periods. The natural questions that now arise are:

(1) How are the microorganisms introduced into the air?
(2) What is the nature of the mixing processes that govern or limit the vertical and horizontal transport of the organisms?
(3) How long can the organisms survive free air conditions?

THE MECHANICS OF EXCHANGE OF MICROORGANISMS BETWEEN EARTH AND ATMOSPHERE

It is assumed that nearly all surfaces, whatever their nature or composition, will contribute to the bacterial population of the atmosphere but that some surfaces, because of greater populations of microorganisms, greater mobility of surface materials or more intense atmospheric turbulence, will contribute far more than others. It is a statistically remote possibility that any single organism in the soil will be lifted by itself into the air; in all

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probability they are most frequently associated with debris of some kind such as bits of organic matter, dust motes or, in the case of marine forms, with salt particles or droplets of concentrated sea water. Thus, with the exceptions of spores and pollen, the organisms in the air must frequently exist as colonies rather than single individuals. The laboratory method of plating and counting the bacteria and molds permits of no distinction between individuals and groups.

In light of such reasoning it can safely be assumed that the processes governing the exchange of soil bacteria between earth and atmosphere are the same as for the exchange of other terrigenous materials. The quantity of material exchanged will be greatest in those areas where: (1) ample supplies of loose particles exist on the surface, (2) surface winds are strong enough to stir up these materials and (3) steep lapse rates exist in the air to favor the vertical transport of the particles. Without the third factor very little surface material will be transported over significant distances although there may be local transport over short distances within the surface layers of air. The supply of microorganisms should be greatest where the surface is dry due to deficient rainfall, where there is an abundance of organic matter in the soil, where intensive cultivation is practiced and in and near wooded areas. The data given by Proctor (loc. cit.) and others appear to bear out these conclusions. A spring maximum of dust in the atmosphere is noted in the solar-radiation measurements in the United States (Wexler, 1936) which is to be expected since the soil is dryest at this season, cultivation is most extensive, surface winds are strongest and the vertical temperature lapse rates are steepest. It can be assumed that the population of microorganisms in the atmosphere would also be greatest during this season for the same reasons.

The processes governing the exchange of bacteria between sea and atmosphere are not wholly analagous to those governing the exchange between soil and air. In the latter case much of the kinetic energy of the air at the surface goes to produce turbulence and is thus available for lifting and transporting the loose surface particles; in the first case most of the energy exchanged through surface friction goes toward producing waves on the sea surface or in initiating and maintaining the flow of surface waters. Except for evaporation, there is no exchange of water between sea and air in such processes. It is only when the waves become unstable or break and spray is formed that any significant exchange takes place and thus it is to be expected that the tidal zone along open coastlines will constitute a primary source of marine bacteria. The spray droplets will, of course, include any bacteria present in the water and upon evaporation may leave the organism associated with a salt particle or droplet of concentrated sea water. Since such hygroscopic particles are extremely effective nuclei for the condensation of water vapor in the atmosphere, they are more readily removed than

are the non-hygroscopic dust particles. In a recent study, Jacobs (1937) determined the amounts of sea salt in the air upon a number of occasions. The collections were made only 200 feet from the ocean high-tide mark and approximately 100 feet above sea level thus they represent the extreme conditions within the tidal zone. The series of 23 analyses gave an average salt content (magnesium chloride and sodium chloride) of 0.38 mg. per cubic meter of air which is equivalent to approximately 0.01 gms. of sea water. Since the number of bacteria in sea water is usually less than 500 per cc. (ZoBell and Feltham, 1934; Benecke, 1933), it can be computed, on the basis of the above salt values, that the number of marine bacteria per cubic meter of sea air will usually be less than 5. The results obtained by ZoBell and Mathews (1936) indicate that this number is too small, however.

On the other hand, the bacteria in a cubic centimeter of soil may be numbered in the millions or hundreds of millions. Proctor (1934), during his determinations of the number of bacteria at high levels, also collected and counted the number of dust particles at the same time. Although he makes no volumetric calculations, rough computations by the writer indicate that he collected approximately 510 visible and collectable dust particles per cubic meter of air averaged for all levels. Above 9000 feet there were approximately 25% fewer particles than the general average. He found the ratio of microorganisms (bacteria and molds) to dust particles to be 1 to 107.95 for all levels and 1 to 117.93 above 9000 feet. The first figure would give 4.7 collectable bacteria per cubic meter of air. Considering the great number of bacteria that must exist in the lowest layers of air, these results show that either a very small percentage of the organisms survive or that the original number is dispersed throughout large volumes of air. By the same reasoning, however, the possibility of encountering even one marine bacterium at these high elevations during a normal collection appears remote.

VERTICAL AND HORIZONTAL TRANSPORT OF MICROORGANISMS

The tendency of turbulence in the atmosphere is to create a uniform distribution of properties throughout the air mass. This action, however, is of far greater magnitude than the mere diffusion of properties between layers; apparently the mixing takes place through motions of eddies or masses which are pushed from their original surroundings at irregular intervals. As stated by Byers (1937, p. 238):

"The significance of these traveling eddies lies in the fact that they carry the properties of their 'mother layer' into the new environment."

Thus it would be expected that microorganisms in the atmosphere, whose

source is at the surface of the earth, would be distributed throughout the atmosphere but that the density would decrease the greater the distance from the source. The biological work to date shows this to be true. For example, Proctor (loc. cit.) notes a general decrease in both dust particles and bacteria with elevation and an increase in the bacterial count in the vicinity of wooded areas, while Rittenberg has just presented data which show a general decrease in the bacteria count the greater the distance from shore. On first analysis, it might be assumed that the number of marine bacteria should increase from the shore seaward but it still remains to be considered that the primary source of marine bacteria is the tidal zone with its foam and breaking waves. The high bacterial counts obtained by ZoBell and Mathews (1936) within the tidal zone are probably much too large for the open ocean.

While the tendency is to create uniformity of properties throughout the air mass, at any given instant this air mass must contain variously large and small masses (eddies) with somewhat different properties than the surrounding air. This reasoning no doubt accounts for at least part of the extreme variability in bacteria counts within small areas, or over short intervals of time, which has been noted by various investigators of the problem and mentioned by Rittenberg. The more intense or prolonged the turbulent action, however, the more nearly will uniformity of properties be approached, although at the same time there must be a general decrease in density of the property relative to the total air mass the greater the distance of the observation from the source area.

If this "uniformity of properties" were actually *attained* in a given region (which would be the case were the process one of pure diffusion), the frequency distribution of mold or bacteria counts per hour would be approximately of the Poisson type, and the ratio of the variance (i. e. mean squared deviation) to the mean of the counts made in the region, should approximatly equal 1.00. A higher ratio indicates the presence of eddy masses which still retain the properties derived from their sources. However, the longer the time elapsed since such an eddy mass left its source, the more completely will its properties become equalized with those of its surroundings on account of diffusion and small scale turbulence, hence the above ratio should diminish for any property with distance from its source.

The region off the coast of California presents unusually stable conditions throughout practically all months, therefore it is not expected that the mixing processes will be as effective here as in many other areas. Nevertheless, the data accumulated by Rittenberg show the above reasoning to be valid. The data in his Table II show that the average mold count[1] per

[1] Rittenberg assumes that all the molds are of land origin regardless of whether they develop on sea water media or tap water media.

hour for the region from 0–100 miles off the coast is 155.6 molds while it is 29.0 molds in the region from 100–400 miles off the coast. Taking the mean of the differences in count between individual stations as a measure of the variability, a value of 250.1 molds per hour is found for the coastal region and 30.8 molds for the region beyond the 100-mile zone. These figures are interesting in that they give ratios between the mean differences in count and mean counts of 1.61 for the first region and 1.06 for the second. However, the actual mixing processes are probably best represented if the ratio of the variance (mean squared deviation) to the mean of the counts is taken. In this case, the ratio is 402.0 in the first region and 32.7 in the second. As suggested, if the mixing were accomplished solely by pure diffusion, the ratios would approach 1.00 in both areas. Approximately the same number of counts were obtained in each of the areas under consideration.

One may speculate as to the origin of these molds. The prevailing winds in the Southern California area are from the sea and thus the air masses usually present over the coastal region are essentially marine in character and may have passed over several thousand miles of sea surface since contact with any land mass. Since the mold collections were made by Rittenberg at intervals of varying length and on several cruises, it may safely be assumed that a large number of the counts were made within true marine air masses. If the molds are primarily of land origin they must have originated either over the continental land masses to the east or over the far removed land areas bordering the North Pacific Ocean on the west or north. It is possible that these microorganisms could have originated in Alaska or Asia but the fact that Rittenberg notes a decrease in the mold counts from shore seaward might indicate that these organisms actually originated from the land surfaces of the United States but were transported westward across the prevailing wind stream through lateral mixing.

Such considerations as those just presented suggest the use of bacterial counts in the identification of air masses. According to ZoBell (1939), it is possible to differentiate between bacteria of marine origin and bacteria of land origin in at least 90% of the cases. If this is true, a determination of the ratio between the two types of bacteria present in the air should indicate whether the air mass is of marine or continental origin and, perhaps, the recency of contact with sea surface. The further identification of particular species of microorganisms, particularly spores and pollens, would permit additional conclusions to be drawn concerning the local movements of small air masses.

The data so far presented indicate the importance of the horizontal and vertical mixing processes in distributing microorganisms throughout the atmosphere. The height to which the microorganisms may be transported

will depend largely upon the degree of stability and the height of the turbulent or convective layer of air. Since the height of the layer of turbulent influence varies as the surface wind speed, roughness of surface and latitude, it would be expected that the vertical transport of organisms will also be governed by these factors. The presence of a discontinuity surface in the upper air will limit vertical transport in either direction resulting in concentrations of foreign particles in the air both above and below the surface. Biologists should look for evidences of similar biologic stratification.

In general, the horizontal transport will be determined by the general stream flow in the atmosphere but lateral mixing along isentropic surfaces will transport the organisms laterally away from the trajectories indicated in the general wind observations. Thus, in these latitudes, the greater transport will be from west to east and, considering the greater carrying power of polar air masses,—from north to south. The horizontal distance over which the individual organism may be transported is almost limitless and is largely determined by its ability to survive the atmospheric environment.

THE ATMOSPHERE AS AN ENVIRONMENT FOR MICROORGANISMS

This question is largely a problem for the biologist but there remain several meteorological factors to be considered. The organisms must first be able to withstand great extremes in temperature, pressure and humidity if they are to survive transport over great distances. It has been argued that solid particles (thus all microorganisms) in the air will radiate and absorb radiation very nearly as a black body and, as a result, they must undergo extreme temperature changes which are not represented by temperature changes within the air mass. However, the heat capacity of the organism, or the particle with which it is associated, must be very small, thus it can be assumed that the temperature of the organism at any instant must be very nearly the temperature of the surrounding air.

Bacteriologists have shown that exposure to ultra violet radiations for short periods is lethal to most bacteria. However, the solid particles to which they are attached may afford some protection against this type of radiation. Nevertheless, the bacteria counts should show a diurnal variation due to this cause.

It has previously been pointed out that Proctor obtained a ratio between bacteria and dust particles of 1 to 107.95 for all levels and one of 1 to 117.93 above 9000 feet. This would show about 8% fewer bacteria per particle for the higher levels which might indicate that this proportion was killed since the physical factors governing their removal from the air would be the same as for the dust particles. He does not give average values for the

layer below 9000 feet, therefore it can be assumed that the proportion that did not survive was somewhat greater than 8%.

CONCLUDING REMARKS

No attempt has been made in these pages to cover the list of possibilities for research in this field; either from the standpoint of the biologist or the meteorologist. The writer merely hopes that the discussion will serve as an added stimulus toward future investigation of the problem by both groups and that it will, in some measure, give guidance to the biologist. It will be the problem of the meteorologist to apply the results of the biological investigations to the atmosphere; it is the problem of the biologist to develop certain and rapid methods for identifying the organisms with respect to type and place of origin.

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DISTRIBUTION OF ORGANIC MATTER IN MARINE SEDIMENTS AND ITS AVAILABILITY TO FURTHER DECOMPOSITION*

By

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It has been shown, in previous contributions (*1*) from this Institution, that the organic matter of the marine bottom has a characteristic chemical composition, similar in many respects to the humus of field and garden soils. This organic matter is not inert but can undergo slow but gradual oxidation, a process shown (*2*) to be largely biological in nature. In shallower bottoms and closer to land, the organic matter was found to be oxidized more readily than that of deep seas. The non-nitrogenous constituents decomposed more readily than the nitrogenous substances, with the result that the carbon-nitrogen ratio of the organic matter tended to become narrower.

In the following experiments, an attempt has been made to extend the above studies, especially with reference to deep sea formations.

The muds used in these experiments were collected on the Oceanographic boats *Atlantis* and *Asterias*, by the use of a modified Ekman mud sampler, 3 inches in diameter and twenty four inches long. The cores of mud varied from 10 to 23 inches in length. The brass section of the mud sampler above the core tube was weighted with molded lead and fitted with a one way valve which prevented water from flushing out the mud as it was being hauled to the surface. The tube containing the mud was disconnected from the rest of the sampler and the mud forced upwards by a modified wooden ramrod which was fastened to the deck. If desired the bottom water directly above the mud with the very light brownish ooze which is ordinarily lost with other types of samplers could be siphoned into a jar and saved for chemical analysis and for oxidation studies. Ordinarily the mud was taken from the core tube in an undisturbed condition. The thin layer of mobile brownish ooze which was sometimes almost slimy was saved together with the highly viscous surface mud and included with the top section; the latter varied from one half to one inch in thickness.

The ramrod was fitted with a collar which could be lowered as desired thus preventing the mud from slipping out of the core tube. This permitted inspection of 3 to 4 inch layers of the mud while being removed. These sections were kept in clean glass jars until used. The sections which appeared to be high in organic matter or with an excess water were stored on ice.

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When brought to the laboratory, the mud was carefully mixed and representative portions suspended in definite volumes of aged sea water. Considerable shaking and stirring with a glass rod was required to suspend the mud. It is believed that this treatment satisfied at least for the moment the chemical affinity which certain marine muds are known to have for oxygen. Among the factors causing this phenomenon are extremely low oxidation reduction potentials, large amounts of hydrogen sulphide, as well as reduced or partly reduced iron present in the mud.

The sea water was collected at considerable distances from land in order to avoid terrestrial contamination. After filtering through several layers of fine silk cloth, the water was stored for at least a month in the dark, then aerated several times, and, after the oxygen reached an equilibrium, used as dilution water.

Aliquot portions of diluted mud were added to several 225 ml. oxygen bottles, as well as to dried filter paper; the latter were dried at 105° C. to ascertain the weight and moisture contents of the sample used. The oxygen bottles were carefully filled with aged sea water. Some of the bottles were analyzed for oxygen after 1 to 2 hours; others were incubated in a water bath in the dark for 5, 10 and 15 days; they were shaken daily for the first 5 days and then every other day. When ready for analysis, the supernatant liquid was siphoned into smaller 125 ml. oxygen bottles and Winkler reagents added. Only the 15 day results are reported in the Tables.

The organic carbon content of the mud was determined by a modification of the Schollenberger method (*1*). Since marine muds, especially the surface of the cores, contain considerable amounts of sea-water, silver sulphate was added to arrest decomposition of the NaCl by the chromic acid. All samples were analyzed in duplicate with and without the addition of silver sulphate. With this modified method, the carbon equivalents of the respective mud were found to be lower by a fraction of a milligram to a few milligrams except in those cases where the moisture content of the mud was very low; the carbon content was then about the same with and without the addition of silver sulphate. Nitrogen was estimated by the Kjeldahl method using potassium persulphate as a catalyst.

The muds used in this study came from 35 to 43 degress North Latitude and from 67 to 70 degrees West Longitude, varying in depth from a few meters to over 5,100 meters. The muds from the higher latitudes were covered with water of arctic origin, whereas the southern muds were covered with highly saline tropical water. Whenever possible, muds were collected in an undisturbed state, and divided into at least 3 sections: top, intermediate and bottom. The respective layers varied from one half to four inches in length. At other times cores were divided into their natural stratified layers. The availability of the organic matter in the mud was calculated on the basis of oxygen consumed per 1 gram of organic carbon in the mud.

Table I gives the results of top sections of cores collected at various distances from land. The sand, water sample and surface material of mud 158 were collected in Dr. Stetson's sand pans. The pans were weighted down so that they could not be easily moved and were fitted with a mechanical device that blocks off the opening into the pan as they are being hauled to the surface. A rope was attached to the pan and to a buoy so it could be found after being allowed to collect sand and silt for a day or so. The yield of sand in any one of these pans was rather small, so that a composite was made of the water and sand in several of these pans. The top water contained considerable amounts of light flocculent materials. This water was siphoned into oxygen bottles and oxygen determinations made after 5, 10, 15 and 34 days. It was found that 1.39 cc. of oxygen was consumed during the first 5 days, increasing to 1.66 cc. in 10 days and to 2.24 cc. per liter in 15 days; the latter figure held after 34 days. The supernatant liquid contained considerable flocculent material, in addition to a certain amount of fine sand; 195 cc. of oxygen were consumed per 1 gram of carbon in this material, while the sand consumed 260 cc. of oxygen per 1 gram of carbon present.

The organic carbon varied from 4.5 per cent in muds collected from Hadley Harbor, Naushon Island, to 0.5 per cent at considerable distance from land. The availability of the organic matter to bacterial decomposition is reported as cc. of oxygen utilized per 1 gram of carbon present in the mud. The oxygen consumption in 15 days varied from 260 cc., in sand collected near shore, to 23 cc. in mud collected at considerable distance from land. The availability of the organic matter in mud 9 containing 4.5 per cent organic carbon was only slightly greater than that of mud 135, which contained only 0.86 per cent carbon. Generally, however, the carbon became less available at greater depths and greater distances from land.

Table I indicates the type of record kept on muds collected off Nomans land. All sections of the respective cores were examined. For lack of space, certain intermediate sections of mud were not reported. These muds showed no significant differences from the layer above or below and served only as additional analysis or to indicate the trend, as determined by biological oxidation and by carbon and nitrogen content.

The first five muds were collected in the immediate vicinity of Woods Hole. Muds 42 to 78 are from Massachusetts Bay, in a line almost parallel to 43° North Latitude going east off the coast of Massachusetts and New Hampshire past the Isle of Shoals to a point about twenty five miles from land. Muds 91 to 111 are a line of stations going east from the northern part of Cape Cod Massachusetts. Muds 112 to 156 were collected along a line from Block Island, Rhode Island to within a hundred and fifty miles from Bermuda.

In order to obtain information on the effect of different types of organic

matter on bacterial decomposition, different sections of the same core were added to oxygen bottles and oxidation studies made. The rate and amount of oxygen consumed can be used as a measure of the availability of the organic matter in the mud. In considering the extent to which the organic matter was attacked by microorganisms only the 15 day period is reported.

One would ordinarily expect that the organic matter in the surface layer of the core would be most easily decomposed, the rate of decomposition gradually decreasing downwards. This was true in about half of the cores examined. In certain cases, as in samples 22, 24 and 25, the top and middle layers were equally available, oxygen consumption being 79 and 82 cc. respectively, whereas the intermediate layer consumed 107 cc. oxygen. In core 42, 44 and 45, the top was least resistant to oxidation, the intermediate most resistant, whereas the organic matter in the bottom layer was somewhat more available than the middle section.

In samples 62 to 66, it was necessary to remove the fine gravel before the mud could be suspended in water. In the top section 1000 cc. of oxygen were utilized per one gram of carbon. This is more than half the theoretical required for complete oxidation of all of the organic matter. This was nearly four times as great as the consumption of oxygen by the mud directly under it and about ten times that of most samples. It is quite probable that this sample of mud contained some fresh animal or fresh plant material.

In muds 91 to 95 the moisture was exceptionally low and the respective layers appeared to be rather homogeneous i. e., without evidence of stratification. The carbon content was rather uniform throughout the entire 15 inches, while the nitrogen decreased from 0.078 to 0.056 per cent in the bottom sample. The maximum oxygen consumption, 198 cc. per gram of organic carbon, occurred in the intermediate layer, it decreased to 86 cc. in the surface and 127 cc. in the bottom. Here again the organic matter which had been buried for some time under anaerobic conditions was two and one half times more easily decomposed than the carbon in the surface mud, while the organic complex in the bottom material was more available than the surface material but only 60 per cent as easily decomposed as the intermediate layer.

Samples 112, 114 and 118 were conspicuous because of the absence of decomposable organic matter below the 5 inch layer. The organic carbon in the top inch was twice as available as that in the next layer. The nitrogen content was uniform namely, 0.03 to 0.04 per cent throughout the core.

Samples 120, 126 and 127, one hundred ninety five miles from land and 2873 meters deep, were decidedly different from the muds 112–118, in that they contained considerable decomposable organic matter. The surface ooze consumed the greatest amount of oxygen.

Samples 142, 145 and 148 were 100 miles from land and 384 meters deep. The oxygen consumed increased from 23 cc. in the top material to 49 in the

8 to 12 inch section and to 105 cc. in the 19 to 23 inch layer. The 15 to 19 inch portion was a whitish clay, whereas the mud, both above and below this layer was sandy, that of the top being coarser than the bottom.

Mud 150 to 156 was in sight of Block Island and 67 meters deep. The top 1 inch layer consumed 55 cc., the 8–12 inch 102 cc. and the 12–16 inch 44 cc., increasing to 113 cc. at the bottom of the core.

Some idea may be gained concerning the nature of the different types of organic matter, if the amounts of oxygen consumed after 15 days are examined. The degree of oxidation depends on the availability of the organic matter. The spread of oxygen consumption is very great varying from zero to 1000 cc. per one gram of carbon present in the bottom sediment. If all the 131 samples tested are put in classes depending on their organic carbon content, it will be found (Figure 67) that there are two distinct groups of sediments. Twenty-five per cent of the muds contained between 0.67 and 0.99 per cent carbon, and 50 per cent contained 0.34 to 1.32 per cent carbon. The other large class of sediments contained 1.99 to 2.31 per cent of carbon, 26 per cent of the samples were within this range, whereas 38 per cent contained between 1.66 and 2.64 per cent carbon.

Similarly if the muds are classified according to the amount of oxygen consumed, it will be seen (Figure 67) that 29 per cent of the sediments utilized between 74 and 93 cc. of oxygen and 76 per cent utilized between 37 and 130 cc.

Since these curves are almost the antithesis of each other, it is apparent that there is no correlation between the amount of oxygen consumed and the amount of organic carbon present in the sediment, except when the carbon is low, namely below 0.3 per cent, when little or no oxygen will be utilized. According to theoretical calculations one gram of organic carbon will utilize 1,860 cc. of oxygen for complete oxidation to carbon dioxide. The oxygen consumption and carbon utilization have been calculated in terms of each other. If the oxygen consumption curve is interpolated in terms of per cent carbon utilization in the respective sediments, it is found that in the case of 29 per cent of the sediments, between 4 and 5 per cent of the carbon was oxidized and in case of 76 per cent 2 to 7 per cent of organic carbon was thus available.

Some idea of the rate of this oxidation may be gained if the oxygen utilization figures are averaged after 5, 10 and 15 days on the 131 samples on which complete oxidation studies were made. In 5 days, an average of 59 cc. of oxygen were utilized in 10 days 83 cc. and in 15 days 112 cc. corresponding to 3.2 per cent of the carbon in 5 days, 4.5 per cent in 10 days and 6.1 in 15 days.

Many of the muds reported in this investigation were analyzed by Waksman and Hotchkiss (*2*) in 1937. They reported the oxygen consumption per 1 gram of dry mud. These data have been recalculated to ascertain the

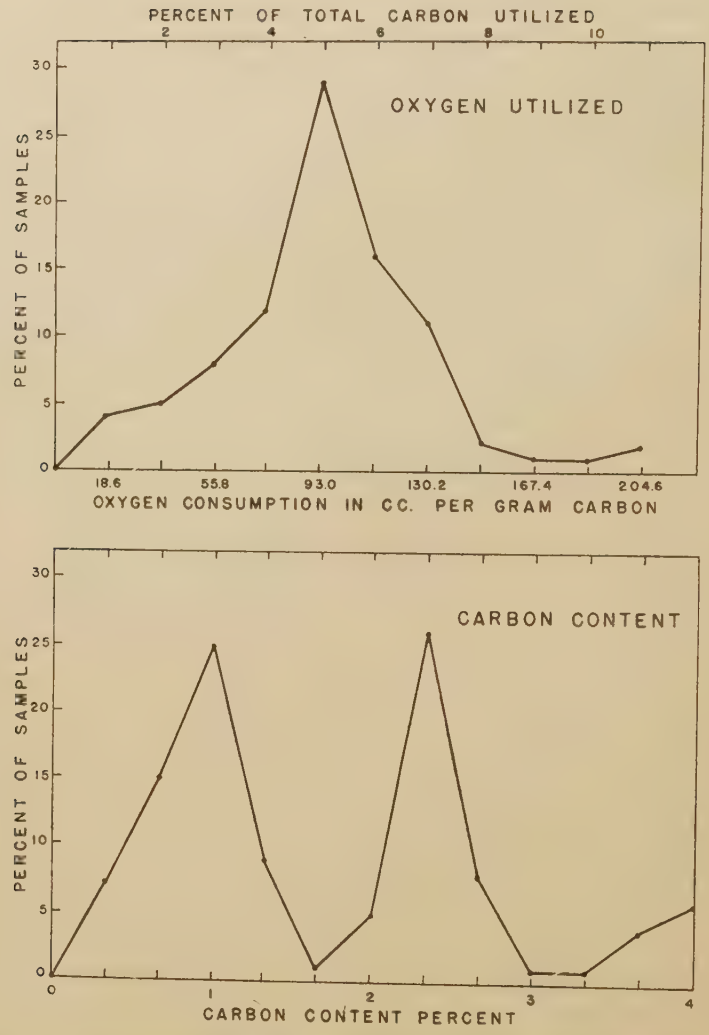

Figure 67. Oxygen consumption, carbon utilization and carbon content of marine mud.

amount of oxygen utilized per 1 gram of carbon present in the mud, compared with the muds collected from the same locality in this present investigation (1938), and reported in Table II. Since only the nitrogen content was reported for the 1937 data, the carbon content was calculated by using the factor 10 : 1. From an inspection of the data in Table I of this report

and from previous reports by Waksman and co-workers the ratio of carbon to nitrogen in most marine bottoms is between 8 : 1 and 12 : 1, a large majority of these being 10 : 1. Muds collected in 1937 and 1938, in a line of stations off the Isle of Shoals, in Massachusetts Bay, and off Cape Cod are compared in chemical composition and availability of the organic matter after 15 days oxidation. The location of these stations and nitrogen content are given in Table 9,[1] Vol. 1, page 114, Journal Marine Research, and are referred to here as station number. In case of Station 1, there was, in 1937, a decrease in oxygen absorption from top to bottom from 80 to 68 cc.; in 1938 (2 cores), there was a similar decrease from top to bottom from about 200 cc. to 92 cc. The nitrogen content of the two samples of 1937 mud was 0.193 and 0.139 per cent, whereas the nitrogen content of the samples taken in 1938 was only about half as large, decreasing from 0.090 and 0.114 at the surface to 0.072 and 0.024 in the bottom of the core.

In Station 2, the oxygen absorbed per 1 gram of carbon increased from top to bottom of the core, namely from 74 cc. to 86 cc. in 1937 and from 166 cc. to 238 cc. in 1938. Here again the surface material contained twice as much nitrogen in the 1937 samples than in the 1938 samples, whereas the bottom material contained about 18 per cent as much nitrogen as the sample collected in 1937.

The surface material in the mud from Station 3 collected in 1938 was very easily decomposed. One thousand cubic centimeters of oxygen were absorbed per 1 gram of carbon. The bottom material utilized 274 cc. of oxygen. In 1937 this mud utilized 70 cc. of oxygen in the surface material and increased to 96 cc. in the remainder of the core. Attention has already been called to the possible abnormality of the 1938 sample.

The mud from Station 4 (1937) increased in oxygen consumption from 47 cc. in the **A** layer to 105 cc. in the **B** layer; in 1938, the top layer utilized 137 cc., the intermediate 91 cc. and the bottom 36 cc. of oxygen. The nitrogen content of the surface material was almost the same during both years. namely 0.252 and 0.272 per cent, decreasing in 1937 in the **B** horizon to 0.192 and in 1938 to 0.136.

In Stations 6, 7 and 8, the organic matter collected in 1938 was more available than that collected in 1937, and was uniform throughout the entire core. Stations 9 to 12 were all from the same vicinity of a 99 fathom hole in Massachusetts Bay. In 1937, the nitrogen content of the top layer of the cores varied from 0.081 to 0.245 per cent. In other words, one sample of mud contained 3 times more than another sample a few meters away. Similarly the nitrogen content in the **B** layer varied from 0.051 to 0.228 per cent. The oxygen consumption per 1 gram of carbon present in the mud fluctuated from 8 to 106 cc. In 3 cases out of 4, the bottom material was

[1] Position reported W. Lat. N. Long. should have been N. Lat. W. Long.

more available than the top by about 2 times. In 1938, two cores were collected from this locality and analyzed. In general, there was a decrease in availability of the carbon from top to bottom. In one case, the middle layer was only half as available as either the top or bottom. One hundred seventy-nine cc. of oxygen were utilized in the top inch, 97 cc. in the 3–6 inch, and 224 cc. in the 10–15 inch section. In one sample the nitrogen decreased from 0.258 per cent in the top layer to 0.168 in the 9–15 inch layer; in another sample the decrease from top to bottom was from 0.126 to 0.040 per cent.

In Station 14, collected off Cape Cod in 1937, 77 cc. of oxygen were utilized in the **A** layer and 153 cc. in the **B** layer. In 1938 there was a similar increase in the availability of the organic carbon from top to bottom, namely 85 cc. in the surface material, 149 cc. in the 7–10 inch layer, and 127 cc. in the 10–15 inch layer. Fifty-four and 55 cc. of oxygen were utilized per 1 gram of carbon in the top and bottom layers of mud from Station 15 in 1937. In 1938, the oxygen consumption was somewhat higher but about the same range, namely 85 cc. in the top and 82 cc. in the 12–15 inch layer. In 1937, the nitrogen content was about the same throughout the core, whereas in 1938 the nitrogen decreased from 0.239 in the top to 0.183 per cent in the bottom layer.

In the mud collected from Station 16, there was an increase in oxygen absorption in the bottom material over the top, both years, namely from 47 cc. to 62 cc. in 1937, and from 64 cc. and 111 cc. in 1938. Here again, the nitrogen was uniform from top to bottom in the 1937 core, whereas, in the 1938, it decreased from 0.182 to 0.157 per cent from top to bottom. In 1938, more oxygen was absorbed per 1 gram of carbon present in the mud from Station 17 than in 1937. The 1938 sample showed a decrease from 111 cc. to 91 cc. in 16 inches, whereas in 1937 the oxidation of the mud increased from 45 cc. to 60 cc. oxygen in the **A** and **B** layer.

The amount of oxygen absorbed per 1 gram of carbon in 14 or 15 days was generally higher in 1938 than in 1937. In certain cases they compare favorably; in other cases the bottom mud was more available than the top one year, whereas the next year the top material was more available than the bottom. No explanation could be offered at present for these differences. Presumably, the experimental procedures were about the same both years. In 1937, the muds were collected in a glass tube about 15 mm. in diameter and the amount of material available for the respective experiments and for chemical analyses, particularly of the top material, was limited. In 1938, however, the muds were collected in a three inch core tube, ten to twenty times more material being thus collected, and should, therefore, be more representative. One may speculate further as to whether a small tube causes the light mobile surface material of the core to be pushed away from the cutting edge of the tube more easily than in the case of the larger tube.

More information is needed concerning the sedimentation of the bottom material and its chemical nature, before the significance of the oxidation of the organic matter can be interpreted.

The author is indebted to Dr. Bigelow and Dr. Renn for permission to use instrument for taking bottom cores and for assistance generously rendered in numerous ways, and to Dr. Waksman, for outlining the problem.

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TABLE I

Chemical and Biological Analysis of Marine Muds

Sample number	*Location*	*Depth, meters*	*Distance from land, miles*	*Layer, inches*	*Moisture, %*	*Carbon, %*	*Nitrogen, %*	*Ratio C/N*	*Oxygen consumed, cc. per 1 gm. carbon in 15 days*
9	Hadley Harbor	6	.02	0–2	72	4.50	.318	14.1	51
11	Hadley Harbor	6	.02	0–1	73	4.32	.350	12.2	66
13	Hadley Harbor			3–8	62	3.33	.252	13.3	47
22	Buzzards Bay	15	2.0	0–½	64	2.35	.220	10.6	79
24	Buzzards Bay			2–4	52	2.10	.195	10.8	107
25	Buzzards Bay			4–6	51	2.46	.197	12.5	82
1	Buzzards Bay	15	1.0	0–½	—	2.11	.220	9.6	82
27	Buzzards Bay	15	2.0	0–8	59	2.16	.262	8.2	62
158	Buzzards Bay	5	.1	water	100	—	—	—	2.2**
158	Buzzards Bay	5	.1	*	92	.73	.076	9.6	195
158	Buzzards Bay	5	.1	sand	15	.11	.020	5.6	260
42	42° 57′ N., 70° 31′ W.	83	11.7	0–2	62	.99	.114	8.7	219

* Supernatant liquid plus ooze.

** Oxygen consumed cc. per liter.

TABLE I continued on next page.

TABLE I—*Continued*

CHEMICAL AND BIOLOGICAL ANALYSIS OF MARINE MUDS

Sample number	*Location*	*Depth, meters*	*Distance from land, miles*	*Layer, inches*	*Moisture, %*	*Carbon, %*	*Nitrogen, %*	*Ratio C/N*	*Oxygen consumed, cc. per 1 gm. carbon in 15 days*
44	42° 57′ N., 70° 31′ W.			5–9	42	.35	.024	14.1	92
45	42° 57′ N., 70° 31′ W.			9–14	44	.46	.032	14.3	128
39	42° 57′ N., 70° 31′ W.	83	11.7	0–1½	60	.84	.090	9.3	195
52	42° 57′ N., 70° 27′ W.	100	14.8	0–1	54	.91	.100	9.1	166
62	42° 57′ N., 70° 25′ W.	100	16.2	0–1	65	.46	.062	7.4	1000
65	42° 57′ N., 70° 25′ W.			13–16	40	.30	.024	12.5	266
67	42° 57′ N., 70° 22′ W.	140	18.3	0–1½	72	2.26	.272	8.3	137
71	42° 57′ N., 70° 20′ W.	159	20.0	0–1	73	2.26	.272	8.3	130
76	42° 57′ N., 70° 18′ W.	164	21.5	0–1	71	2.31	.246	9.4	103
77	42° 57′ N., 70° 18′ W.			1–3	57	2.23	.212	10.5	143
78	42° 57′ N., 70° 18′ W.			9–12	57	2.20	.242	9.9	117
81	42° 59′ N., 70° 15′ W.	155	22.7	0–1	74	2.30	.271	8.5	112
86	42° 59′ N., 70° 12′ W.	175	24.9	0–1	68	2.35	.252	9.3	90
29	42° 30′ N., 70° 18′ W.	168	16.5	0–½	71	2.34	.258	9.1	95
34	42° 30′ N., 70° 18′ W.	160	16.5	0–1	68	1.16	.126	9.2	197
36	42° 30′ N., 70° 18′ W.			3–6	34	.67	.062	10.8	97
38	42° 30′ N., 70° 18′ W.			10–15	42	.48	.040	12.0	214
91	42° 00′ N., 69° 46′ W.	150	12.9	0–½	42	.60	.078	7.7	85
93	42° 00′ N., 69° 46′ W.			3–7	34	.57	.052	10.9	198
95	42° 00′ N., 69° 46′ W.			10–15	30	.66	.056	10.8	127
97	42° 01′ N., 69° 43′ W.	165	14.3	0–1	73	2.06	.232	8.9	111
107	42° 01′ N., 69° 38′ W.	210	17.9	0–1	68	1.78	.182	9.8	64
111	42° 01′ N., 69° 38′ W.			13–16	57	1.77	.157	11.3	111
102	41° 59′ N., 69° 41′ W.	168	13.6	0–½	73	2.02	.239	8.9	85
106	41° 59′ N., 69° 41′ W.			12–15	58	2.19	.183	11.9	82
157	40° 37′ N., 71° 38′ W.	67	30	*	92	.94	.144	6.5	110
150	40° 37′ N., 71° 38′ W.			0–1	62	1.14	.116	9.8	55
153	40° 37′ N., 71° 38′ W.			8–12	38	.56	.092	6.1	102
154	40° 37′ N., 71° 38′ W.			12–16	42	.10	.090	11.4	44
156	40° 37′ N., 71° 38′ W.			19–22½	34	.10	.076	13.2	113
149	40° 13′ N., 71° 27′ W.	85	55	0–8	51	.49	.046	10.7	119
142	39° 57′ N., 71° 11′ W.	384	100	0–1	70	1.30	.142	9.2	23
145	39° 57′ N., 71° 11′ W.			8–12	37	.87	.082	10.6	49
148	39° 57′ N., 71° 11′ W.			19–23	38	.80	.072	11.1	105
140	39° 39′ N., 70° 53′ W.	2285	120	0–½	54	.86	.106	8.1	40
128	39° 17′ N., 70° 28′ W.	2800	150	0–½	65	.94	.058	16.2	23
127	39° 00′ N., 70° 16′ W.	2873	195	*	89	.85	.054	15.8	132
120	39° 00′ N., 70° 16′ W.			0–1	69	.73	.083	8.8	23
126	39° 00′ N., 70° 16′ W.			16–19	53	.86	.072	11.9	80
119	35° 05′ N., 67° 05′ W.	5233	450	*	89	.86	.066	13.0	23
112	35° 05′ N., 67° 05′ W.			0–1	49	.57	.036	15.8	51
114	35° 05′ N., 67° 05′ W.			5–8	46	.33	.030	11.0	0
118	35° 05′ N., 67° 05′ W.			17–20	47	.24	.038	6.3	0

TABLE II

COMPARISON OF OXYGEN CONSUMPTION AND CHEMICAL COMPOSITION OF BOTTOM MATERIALS FROM A LINE OF STATIONS OFF MASSACHUSETTS BAY, ISLE OF SHOALS AND CAPE COD, COLLECTED IN 1937 AND IN 1938

Station No.	*Layer*	*1937 Carbon % (calc.)*	*Oxygen consumed*[1] *cc.*	*Section inches*	*1938 Nitrogen %*	*Carbon %*	*Oxygen consumed*[1] *cc.*
1	A	1.93	80	0–1½	.090	.84	195
				0–2	.114	.49	219
	B	1.39	68	5–8	.072	.68	94
				5–9	.024	.36	92
2	A	2.09	74	0–1	.100	.91	166
	B	1.73	86	9–12	.032	.44	238
3	A	1.38	70	0–1	.062	.46	1000
	B	.48	96	9–13	.018	.27	274
4	A	2.52	47	0–1½	.272	2.26	137
				4–8	.162	2.14	91
	B	1.92	105	8–14	.136	2.04	36
5	A	2.91	42	0–1	.272	2.26	130
				6–9	.218	2.38	91
	B	2.54	54	9–12	.224	2.35	115
6	A	3.06	33	0–1	.246	2.31	103
	B	2.72	46	9–12	.242	2.20	117
7	A	2.88	55	0–1	.227	2.30	112
	B	2.27	58	9–13	.210	2.17	107
8	A	3.26	57	0–1	.253	2.35	90
				8–12	.150	2.21	94
	B	.81	38	12–16	.168	2.17	108
9	A	.81	8				
10	A	1.79	49	0–½	.258	2.34	95
				2½–5	.172	1.99	81
	B	.51	92	9½–15	.168	1.98	82
11	A	1.62	51	0–1	.126	1.16	197
				1–3	.124	1.00	81
	B	1.76	106	3–6	.062	.67	97
				6–10	.042	.63	112
12	A	2.45	54	10–15	.040	.48	204
	B	2.11	69				
14	A	.81	77	0–½	.078	.60	85
				7–10	.050	.69	149
	B	.47	153	10–15	.056	.66	127
15	A	2.60	54	0–½	.239	2.02	85
	B	2.61	55	15–15	.183	2.19	82
16	A	2.33	47	0–1	.182	1.78	64
	B	2.34	62	13–16	.157	1.77	111
17	A	2.26	46	0–1	.232	2.06	111
	B	2.04	60	12–16	.182	1.85	91

[1] Per 1 gram of carbon present in mud, in 14 days in 1937, and in 15 days in 1938.

THE CORRELATION OF WATER MOVEMENTS AND DISPERSAL OF PELAGIC LARVAL STAGES OF CERTAIN LITTORAL ANIMALS, ESPECIALLY THE SAND CRAB, EMERITA*

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INTRODUCTION

The great rôle played by water currents in the dispersal of marine animals has long been recognized and put to use in the explanation of animal distribution both planktonic and benthic. Conversely the pelagic animals may in some instances be very useful as indicators of the source or nature of the water movements. Many years ago, Cleve (1900) recognized this fact in his investigations of passively floating life but failed to fully distinguish between geographic and biological groups (Gran 1902). Nevertheless the principle of his hypothesis is good as expressed by Cleve-Eulser (1928) in the following: "regular biological analysis of the oceans and of the coastal waters would no doubt give a more thorough knowledge of the sea currents, their movements and their intermingling, than could be expected from hydrographic observations only."

Obviously most information could be gleaned from the drift of the pelagic larvae of a sedentary animal with a known restricted distribution, or any population spawning in a restricted area, provided the larval stages taken in the plankton can be with certainty recognized, and provided that the duration of the various pelagic stages is known approximately. Thus the spacial and time factors could be determined within reasonable limits. This would be an ideal situation (comparable to the release and recovery of innumerable drift bottles) and one not met with in most instances.

A study of the dispersal of the pelagic larvae of the sand crab *Emerita analoga* (Stimpson) appears to be particularly useful in illustrating the significance of water movements in the life of an intertidal benthic animal, and at the same time to give direct corroborative evidence of some features of general circulation and lateral mixing of water off the coast of southern California.

* Contribution from the Scripps Institution of Oceanography. New Series, No. 79.

In the post larval and adult state, *Emerita analoga* inhabits sandy beaches where it burrows just under the surface of the sand, forming aggregations of several square meters in extent and with great concentrations of individuals. The aggregations are however, quite scattered. The favorite locations are on exposed beaches at, or above, the low tide level where the wash of wave and surf is especially active. This species is one of two *Emerita* species occurring on the west coasts of North and South America. Schmitt (1935) gives its range of distribution from Oregon (Holmes); Drake Bay, California to Magdalina Bay, Lower California; and from Salavery, Peru to Lota, Chile. The second species, *Emerita rathbunae* Schmitt, is said to range from La Paz, lower California to Capon Peru. Related forms occur in other tropical and subtropical regions of the world.

The animals obtain food through the action of the intermittent waves, screening out microorganisms in the passage of water over their plumose antennae which protrude from the surface of the shifting sand (Weymouth and Richardson, 1912). The structure of the antennae is such that most efficient feeding occurs with the receding wash of the breakers and the animals tend to maintain themselves at a tide level where the maximum wash occurs (MacGinitie, 1938). It is probable that this habit of intertidal feeding is a deciding factor in limiting the animals to the wave washed zone of clean sandy shores.

During the breeding season the females carry the eggs attached to the abdominal appendages, hence a study of the occurrence of oviferous females gives a good indication of the season of maximum reproduction. From such a study, our local species has been shown to have the height of its mating season during May and June, though a few oviferous females may be found throughout the year (MacGinitie 1938).

The eggs are incubated through the cleavage and embryonic stages while yet attached to the female, and the larvae are finally released as free-swimming organisms in the first zoeal stage. Beyond this, no study has been made up to this time pertaining to the further development and fate of the weakly swimming larvae of our species *Emerita analoga*.

As a result of a special study (an account of which will be published elsewhere) of the developmental stages, it is now possible to identify with certainty the various stages as taken in general plankton surveys. With this information at hand a study of the distribution of the various pelagic zoeal stages, of which there are five, was undertaken in order to trace as nearly as possible the offshore dispersal resulting from seaward transport by water currents. The survey was made during five of six cruises of the *E. W. Scripps*, research vessel of the Scripps Institution of Oceanography, conducted at approximately two month intervals during 1938. Plankton samples were collected regularly (weather permitting) at all hydrographic stations distributed along four, east-west lines or sections extending from the

coast seaward to about 150 to 180 miles, and from San Luis Obispo to San Diego (Figures 68–71). The net employed was a 70 cm. Nansen net three meters long and constructed of Nos. 000, 0 and 8 bolting cloth. The standard collections were taken vertically from 200 meters to the surface. Most larvae were caught during late summer and autumn as shown by the following summary of successful stations.

Cruise I. February 15–25. No net hauls were taken.

Cruise II. April 8–12. Only 7 stations were occupied due to rough weather. None successful for larvae.

Cruise III. June 7–18. 25 stations sampled, one successful for larvae.

Cruise IV. Aug. 16–26. 34 stations sampled, 13 (38%) successful for larvae.

Cruise V. Oct. 26–Nov. 5. 28 stations sampled, 10 (36%) successful for larvae.

Cruise VI. Dec. 9–18. 27 stations sampled, 6 (22%) successful for larvae.

Since it is known that the larvae of *Emerita* are released in the immediate vicinity of sandy shores, their presence in older stages in offshore situations must have resulted from a seaward drift of waters which have bathed the sandy shores within the period of time required for the larvae to advance from the first zoeal stage to the more advanced stages in which they are taken in their offshore locations. The larvae are only weak swimmers, unable to stem water currents of any appreciable magnitude. Their swimming, weak as it is, must, however, for a time be sufficiently directed by positive reaction to light or negative reaction to gravity, to contribute to keeping them in suspension for a considerable period of time. Eventually however, the time for metamorphosis is reached or the over-heavy carapace forces the animals to seek the bottom, there to live the remainder of their lives, if conditions be suitable, i. e., sandy open shore line. If, however, conditions are unfavorable due to great depth of water or unsuitable substratum at the point where they have deserted the planktonic life, they must succumb. The study of the larvae of *Emerita* doubtless demonstrates dramatically the fate that overtakes vast hordes of larvae of intertidal forms. This, however, is the price paid for the widest possible lateral dispersal.

Just how far *Emerita* can be transported in the larval stages before succumbing is not shown in this investigation but it may be significant that at the most distant offshore stations only zoeal Stage III and IV were found, while the last zoeal stage, i. e., Stage V, was seldom taken and then only relatively near shore. This may mean that any larvae that have been transported for a period of time sufficient to reach the fifth stage have sunk to a depth greater than that fished by the net. It is, of course, also obvious that each successive stage must contain fewer individuals due to hazards of existence. Thus the likelihood of being caught is diminished accordingly, unless the greater length of time in existence has resulted in greater dispersal

within the water masses characterized by the larvae as appears to be the case with Stage IV. Stage V may also be of relatively short duration.

FIELD OBSERVATION

Zoeal Stage I was taken only at stations situated relatively near shore on the inshore end of the sections (Figure 68, Stations 2, 13 and 31). The farthest seaward of these is Station 2, located 20 miles from the nearest shore. Hence the duration of zoeal Stage I is sufficiently long in nature to

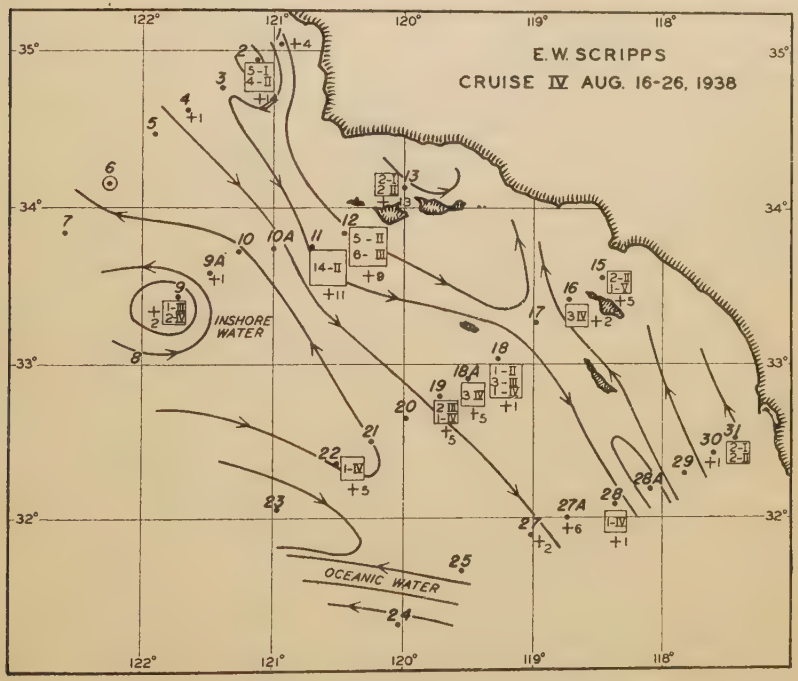

Figure 68. Dispersion of larvae: Figures within the squares indicate the number and zoeal stages of *Emerita analoga;* the symbol + followed by a number indicates the number of unidentified crab larvae. The lines in the chart represent calculated lines of flow which, like the indicated water masses, are based on temperature and salinity distribution. The circled stations were not occupied for plankton.

allow at least a 20 mile drift, and very likely much more, since with the main currents usually paralleling the shore in that area, it would be highly unlikely that the zoeae caught at a given point, originated at the very nearest shore. Reference to the hydrography of the area near Station 2, during Cruise IV, indicates that the flow of water inside the station had a

velocity as high as 25 cm/sec. It is perhaps important to note, however, that Station 2, where a group of young larvae were taken, is located precisely within what appears to be an eddy, which would contribute much to slowing up their transport. In cultures grown in connection with the above mentioned study of developmental stages of *Emerita*, it was shown that under experimental conditions the first zoeal stage may last up to four or more weeks. It is probable though that the time required to complete each

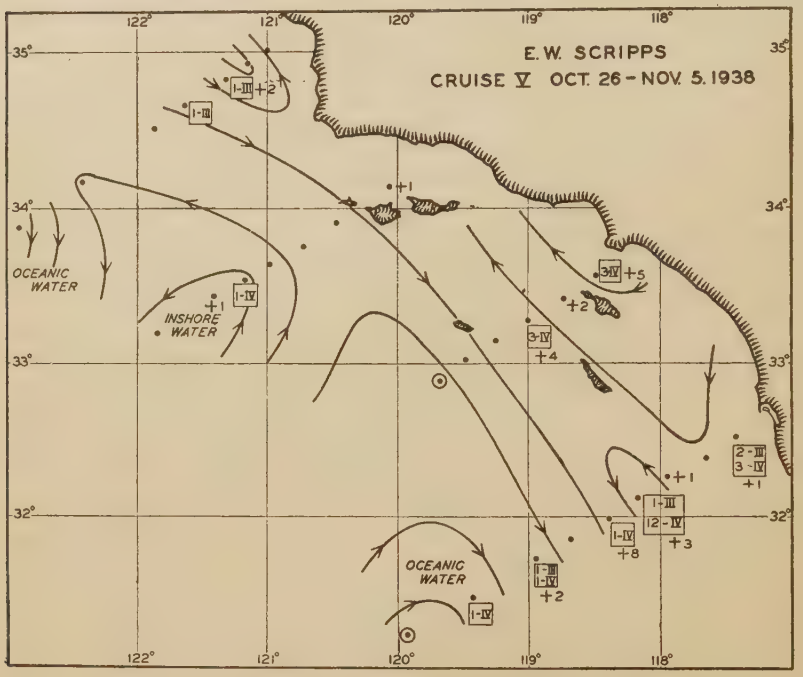

Figure 69. Dispersion of larvae: Explanation as in Figure 68.

developmental stage is considerably less in nature, following more rapid growth due to a more favorable source of food. In experimental cultures difficulty was experienced in feeding. The reason for the low frequency of successful catches of Stage I, is probably due to the fact that by far most of the stations are located over 20 miles from the mainland shore, and therefore, out of the main Stage I distribution.

Zoeal Stage II also occurred mainly at stations relatively near the coast. The largest numbers (14) taken at one time were at Station 11, which is situated about 25 miles outside of the Channel Islands, thus indicating a somewhat wider dispersal for this stage over Stage I. The notably success-

ful catches of Stage II at Station 11 and 12 may well contain larvae originating from the nearer of the islands, though the slow flow of water near these islands showed a movement mainly to the south, forming a large eddy at the outer edge of which the above stations were located (Figure 68).

Zoeal Stage III occurred at various stations, the most distant seaward being at Station 9 and 28, about 80 and 65 miles from shore (islands) respectively.

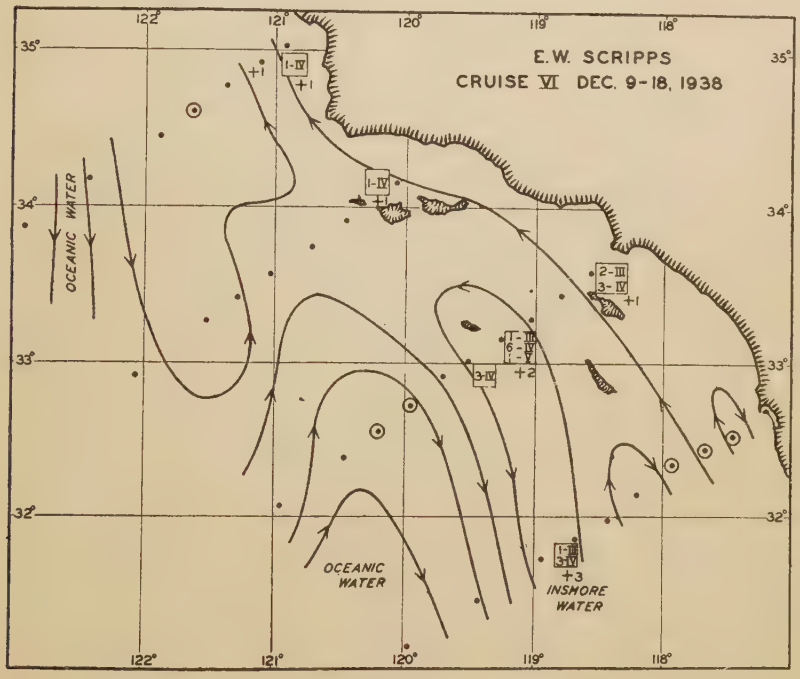

Figure 70. Dispersion of larvae: Explanation as in Figure 68.

Zoeal Stage IV was most widely dispersed of all, being taken at the outside Stations 9, 22, and 25, which are respectively *80*, *70*, and *90* miles from the nearest island shore; but also other distant stations, especially along the southern line, yielded the larvae in Stage IV. From the mainland shores, the most distant seaward of successful stations are 125 and 130 miles, and though the possible island origin of the larvae cannot be neglected, yet the likelihood of originating on the mainland shores is far greater. Not only was zoeal Stage IV widely distributed but the frequency of successful stations at which it occurred was twice that of any other stage. This

frequently resulted not from a greater number of successful stations in restricted areas, but on the contrary, from successful stations widely distributed, indicating that they perhaps result from an actually wider dispersal of Stage IV of the larvae.

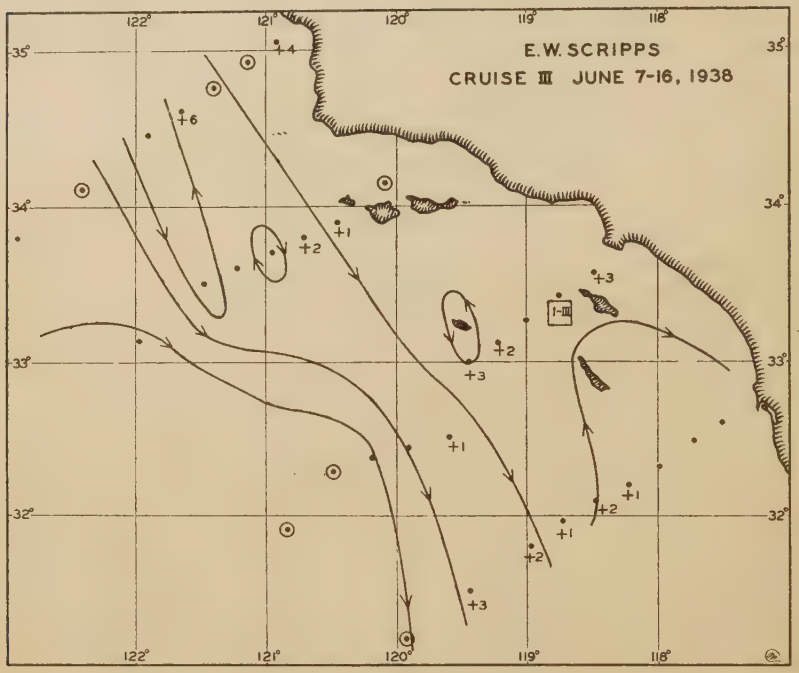

Figure 71. Dispersion of larvae: Explanation as in Figure 68.

Zoeal Stage V. Larvae in this stage were extremely scarce, only two being taken in the regular cruises. These occurred at the relatively nearshore Stations 15 and 18. As mentioned above, this dearth of Stage V may result largely from the sinking of the now relatively heavy larvae in anticipation of desertion of the pelagic existence.

RELATION TO HYDROGRAPHIC CONDITIONS

The hydrographic features based on observations taken during the same cruises have been discussed by Fleming (Sverdrup and Staff, in press) and Sverdrup and Allen (1939). Here only the general character of the currents and the water masses are presented in simplified form in Figures 68–71 from the hydrographic computations. In comparing the plankton stations that

were successful for *Emerita* larvae with the approximate lines of flow (reflecting temperature and salinity relationships), some interesting correlations are brought out.

The wide distribution of *Emerita* larvae, as shown by this study, is striking corroborative evidence of the effectiveness of seaward transport of coastal waters in this area, for it is only by some type of offshore movement of large masses of water, that the larval distribution could be effected. Figures 68–71 show a number of eddies that carry water more or less directly to or from the coast but the main movements are mostly parallel or oblique to the coast line, a fact which may result in considerable lapse of time in carrying the larvae to the outer stations.

Some of the hydrographic relationships have already been pointed out in connection with the discussion of the separate larval stages. It is noted that single or groups of successful stations show a tendency to fall within more or less well defined eddies or tongues of water of inshore character. Cruise IV, Stations 9 and 22 are striking examples of this; with the former station appearing near the center, and the latter in an extension of this isolated inshore water. Station 2, which yielded more larvae than any other station on this line at any time, is also within an eddy of inshore water. A similar picture is shown in Cruise V, Station 9A, and at Station 28A; the first being of special interest because of its offshore isolation, and the second because of its greater yield of larvae. With the exception of Cruise V, Station 25, all other successful stations were within currents characterized by inshore water. Station 25 is situated within an eddy of oceanic water. This may indicate a small admixture of inshore water too small to be detected by the chemical physical analysis, or an earlier shift of the larvae by swimming from a layer of inshore water to an adjacent layer of offshore water at a well defined contact zone. At all other stations indicated on the charts where oceanic water prevailed, such as for instance the outside stations of the first and fourth lines, no larvae were found.

The number of larvae taken is small but in dealing with an animal like *Emerita* which is limited in habitat and which produces relatively few eggs, large numbers of pelagic larvae obviously cannot be expected to be caught even if the amount of water filtered in one haul be much larger than that in our samples. The numbers are sufficiently characteristic with respect to stages and regional and seasonal distribution to strongly suggest actual relative conditions. The absence of larvae from a haul does not, of course, indicate their total absence at the station sampled, but the presence of larvae even in small numbers is significant in view of their restricted coastal origin. Therefore, the frequency of successful stations becomes of prime importance.

Unfortunately a statement as to the length of pelagic existence can at this time be only an approximation. Certainly it is relatively long, perhaps

about four months. This appears also to be compatible with the findings of Menon (1933) for the Asiatic species in which the seasonal distribution of developmental stages would indicate that the duration of the pelagic life may be a matter of about four months.

This rather long period of pelagic existence allows time for transport over many miles along the main flow of water currents. But it should be noted that a great deal of lateral mixing of water within the area must also have occurred as indicated by the completeness of the scattering that has taken place in view of the restricted origin and numbers of larvae produced. Designating the lines of station as 1, 2, 3 and 4 from north to south we find the following per cent of hauls yielding one or more larvae:

Line 1, 19 hauls, 21% successful for larvae; line 2, 22 hauls, 27% successful for larvae; line 3, 23 hauls, 48% successful for larvae; line 4, 23 hauls, 35% successful for larvae.

The following summary of the relative extent of dispersion of the various stages also indicates a greater thoroughness of scattering of the older stages III and IV owing to the greater length of time that they have been in existence. Of the total number of stations successful for *Emerita* larvae, 10% yielded Stage I, 24% yielded Stage II, 41% yielded Stage III, 72% yielded Stage IV, and 7% yielded Stage V.

A probable explanation for the small percentage of yield of Stage V has already been given above.

OTHER CRAB LARVAE

A fair number of crab larvae (brachyurous type) other than *Emerita* were also present in the hauls. These, unfortunately cannot at this time be identified as to species, so it is not possible to know with certainty whether they are the young of crabs living in shallow water near shore or of species inhabiting or spawning in deep offshore water. When the larval distribution is plotted, however, we find it to be strikingly similar to that of the *Emerita* larvae. Usually they occurred at the same station with *Emerita*, but when caught alone they were always at neighboring stations or, as in one instance, at an isolated inshore station (See Figures 68–71 for distribution and numbers). The stations yielding most *Emerita* usually were also those most productive in other crab larvae. This close agreement with the locality records for *Emerita* strongly suggests inshore origin also for the unidentified larvae.

During Cruise III only one *Emerita* larva was taken while other crab zoeae were moderately well represented, but here it is not clear just what relations there are with the hydrographic conditions, except that all stations yielding larvae were inshore to the main flow of water (Figure 71).

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